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MEASURING TOD OVER A REGION USING GIS BASED MULTIPLE CRITERIA ASSESSMENT TOOLS

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ABSTRACT

Transit Oriented Development (TOD) is one of the promising planning approaches to stimulate sustainable development. Planning for transit oriented development must consider the existing TOD levels that indicate the degree to which a development is oriented towards the use of transit. These TOD levels can be measured using an index called 'TOD Index'. High TOD index values and hence high TOD levels imply that the urban development at that location has high orientation towards use of transit. Using *the TOD Index, it is intended to identify areas of high TOD levels but poor access to transit. Our TOD index measures multiple spatial indicators and aggregates them using spatial multi-criteria analysis (SMCA) to arrive at a comprehensive value depicting the existing levels of TOD at a location or an area. The proposed TOD index was used for the Region of Arnhem and Nijmegen in the Netherlands. Since the SMCA framework requires stakeholders to indicate which indicators are more important than others, various stakeholders from the city region were consulted. Using the TOD index, TOD levels were then measured over the entire city region covering approx. 1,000 km*^{2}*. To test the robustness of the index, a sensitivity analysis was carried out. We then used spatial statistical analysis to create hotspots of high TOD index values. Using the PTAL (Public Transport Accessibility Level) index, we further carved out those areas of the hot spots that have acceptable levels of access to public transit. The remaining areas of hot spots are thus, finally proposed for better transit connectivity.*

Key words: *Transit Oriented Development, TOD, TOD Index, Measuring TOD, SMCA, Arnhem and Nijmegen Region*

1. INTRODUCTION

Transit Oriented Development (TOD) is typically an urban development that features high densities, diverse land uses, and a walkable environment as it has been defined by various authors before (Calthorpe (1993), Boarnet, et al. (1997), The City of Calgary (2004), Schlossberg, et al. (2004), Dittmar (2004), Parker, et al. (2002) and CTOD (2009). These characteristics encourage the people to use transit and by doing so various benefits of TOD can be achieved. Some of these benefits are increased access to transit and hence opportunities, utilisation of already developed land, reduced vehicular pollution, healthier lifestyles and financial and economic benefits from the same.

For effective TOD planning, it is important to be able to assess the existing situation by measuring the existence of TOD characteristics at a certain place. To achieve the same we make use of a TOD index that measures the typical TOD characteristics in an area. A detailed study of previous work on TOD (Cascetta, et al. (2008), Renne (2009), Boarnet, et al. (1997, Loo, et al. (2010, Parker, et al. (2002), Howe, et al. (2009), Chorus (2009), Schlossberg, et al. (2004), Arrington (2009) revealed that this has not been attempted before. The need for such an index was also identified by Evans, et al. (2007). Using this index we measure TOD over our case study – City Region of Arnhem and Nijmegen, The Netherlands. The officials of the region also wish to use TOD principles in achieving sustainable development and associated benefits of TOD.

As a part of TOD planning, we wish to measure TOD across the whole region and identify hot-spots or areas of high TOD index values, that have poor access to transit, in spite of their high TOD levels resulting from existing urban patterns. As Calthorpe (1993) has mentioned, TODs can be developed without proximity to transit but justifiable focus on pedestrian and healthy communities. Thus, existence of TODs is not dependant on its proximity to transit. Planning for TOD, thus, should also not only be about making the areas surrounding transit nodes, more transit oriented. Rather, it should also mean taking transit to those locations where TODs exist, but transit doesn't. With this belief, we work on measuring TOD across our case study at a regional scale. Our approach can help in improving the public transport system by providing better access to transit, opportunities and hence better economic development to deserving areas (Singh, et al., 2014).

Thus, our approach innovates on two levels: first is to measure TOD using and index and the second is to understand TOD from a different point of view, i.e. improving transit access to areas where development is already transit oriented, rather than making the development around existing transit nodes more transit oriented. Our methodology for the same includes measuring a number of TOD indicators spatially over the entire region and using Spatial Multi-Criteria Analysis (SMCA) to arrive at a TOD index value. In this process, we also involve the stakeholders for weighing the indicators with respect to their importance for TOD. Further, we identify the hot-spots spatially and assess their access to transit.

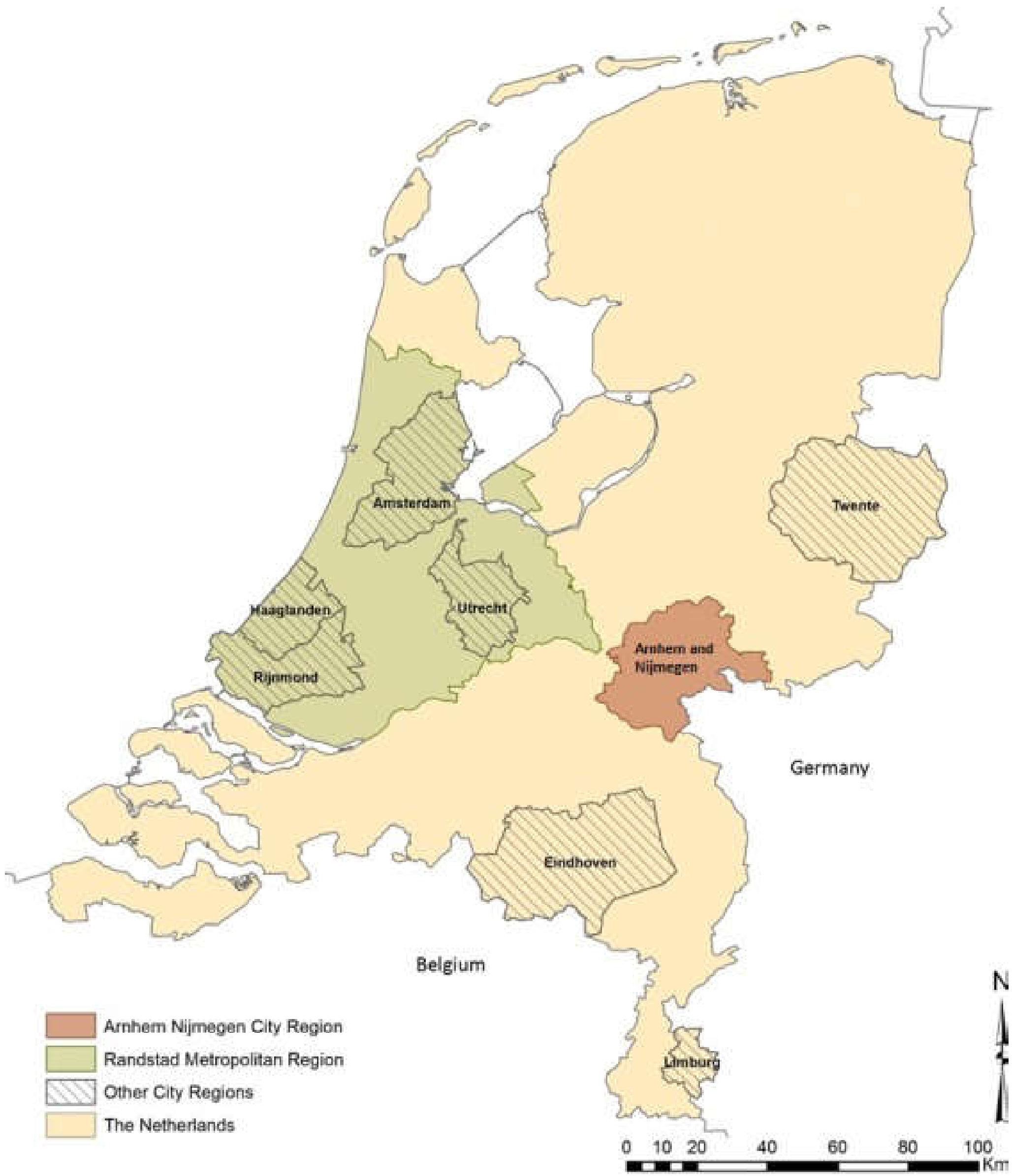
2. METHODOLOGY

Measuring TOD requires firstly the identification of appropriate indicators. There is abundant literature available on the indicators that can be used for evaluating the performance of a TOD project (Schlossberg, et al. (2004), Renne (2009), Evans, et al. (2007), Belzer, et al. (2002), The City of Calgary (2004), Cervero, et al. (2009), Cervero, et al. (1997), Zhang, et al. (2006), CTOD (2011)). Based on the literature, four main criteria were listed that are important to measure TOD – density, land use diversity, walking and cyclability encouraged by the urban design; and economic development. Within those criteria, following indicators, a mix of spatial and non-spatial, were chosen to measure TOD such that they cover the different aspects of TOD sufficiently while being measurable and quantifiable at the same time.

1. Criteria: Urban densities
    a. Residential density (number of persons /km^2)
    b. Commercial density (number of commercial enterprises/ km^2)
    c. Employment density (number of employees/ km^2)
2. Criteria: Land use diversity
    a. Land use diversity measured using entropy index
3. Criteria: Walkability and Cyclability
    a. Intersection density (number of intersections/ km^2)
    b. Total length of road fit for walking and cycling (km)
    c. Mixedness of residential land use with other land uses
4. Criteria: Level of economic development
    a. Density of business establishments (number of business establishments/ km^2)
    b. Tax earnings of municipalities (thousand Euros in last year)
    c. Employment levels

For using our TOD index to measure TOD levels, we worked on the City Region Arnhem and Nijmegen (‘City Region’ hereinafter) (Fig.1) in the Netherlands which is one of the eight regions in the country. The City Region officials aim to reduce the car dependency in their region by promoting public transport. This work fits with their objectives in finding those areas where transit may be required but is not present sufficiently. The City Region has 20 municipalities and a population of about 7,35,000 persons. There are two main urban centres in the region – Arnhem and Nijmegen and most urban development is concentrated around these cities. In the City Region, main transit system is the rail based transit that has 21 existing stations in the region and BRT has only started to evolve as only one line is said to be operational. Regular buses also ply in different urban areas of the region.

Fig. 1 The Arnhem and Nijmegen City Region, The Netherlands



The TOD index needs to be measured over the entire region to see how index values vary from one location to another and if there are some areas where TOD level are already high. Thus, we need to divide the City Region into a number of grid cells such that TOD index can be calculated for each grid cell ensuring that the cell size is neither too big nor too small. Using tessellation of space, different grid tessellations of 100 x100m, 200x200m, 300x300m and 500x500m were tested. While the cell size of 100x100 were too small and resulted in low computational performance, the cell size of 500x500m was found to be bigger than ideal. Thus, 300x300m was chosen for the grid size and overlaying this grid over the region's 1,000 km^2 of area resulted in more than 12,000 grid cells. The TOD index was calculated over all of these grid cells. The detailed calculation of all indicators has been given in section 3.

After the indicators have been calculated, they need to be comprehensively aggregated into an index value for each grid cell. For this purpose, we make use of Spatial Multi-Criteria Analysis (SMCA) as all our indicators have different units of measurement and are a mix of spatial and non-spatial indicators. SMCA combines multiple criteria or indicators and the results can be finally shown on a composite map. The ILWIS software (ITC, 2007) was used for SMCA such that input data are raster maps for all indicators and the output is one composite index map showing the TOD index value for each grid cell in the City Region. Due to the complexity of dealing with multi-dimensional spatial indicators, indicators need to be standardized. They can also be assigned 'weights' indicative of their relative importance to the concept of TOD and its realisation. For weighing the indicators, a workshop was held with the municipal heads of all 20 municipalities, where they were asked to rank the indicators in order of their importance in realisation of TOD. The ranks thus awarded by them were aggregated using the Borda Count Method (Reilly, 2002) and used to assign weights to the indicators. The processes of standardisation and weighing of indicators have been detailed in section 5. At the end of SMCA, TOD index results are received for all grid cells over the City Region. A sensitivity analysis was carried out to confirm the robustness of our results.

In order to find areas or clusters of high TOD index value, we employed spatial statistical techniques of 'Getis Ord Gi*' and 'Anselin Local Moran's I' to spatially identify and locate the clusters of high TOD index values, that we call the 'hot-spots'. What is left then is to assess the access to the transit. It will help in identifying those hot spots that have poor access to transit even though they possess TOD characteristics. Public Transit Accessibility Level (PTAL) method (TfL, 2010) was used to assess the access to transit. The identification of hot-spots and PTAL have been detailed out in section 7.

3. RESULTS OF MEASURING INDICATORS

The data required for measuring various indicators, statistical and spatial, was collected from various credible secondary sources like Central Bureau for Statistics (CBS), the office of City Region Arnhem and Nijmegen, TOP 10 NL - ESRI Nederland and Open Street Map (OSM). Only the data for tax earnings per municipality and the employment levels could not be collected and hence were dropped. This section elaborates the detailed calculations of indicators and their results.

3.1 Population Density

Population density was computed as number of persons per km^2 based on population data per neighbourhood, taken from the CBS. Since our area of analysis i.e. 300x300m grid cell does not conform to neighbourhood boundaries, the ArcGIS function on data apportionment for non-coterminous polygons was carried out to proportionately divide population per neighbourhood into the area of analysis. This function used the building foot-print data that we had for land use information. Thus, data apportionment was based on the proportion of land covered by residential building foot-prints in the area of analysis and the neighbourhood. The population density map for the City Region is shown in Fig. 2.

3.2 Commercial Density

The commercial density was calculated as number of commercial enterprises per km^2 and the procedure for this was same as that employed for population density, except here, the building footprints of commercial buildings were used for data apportionment.

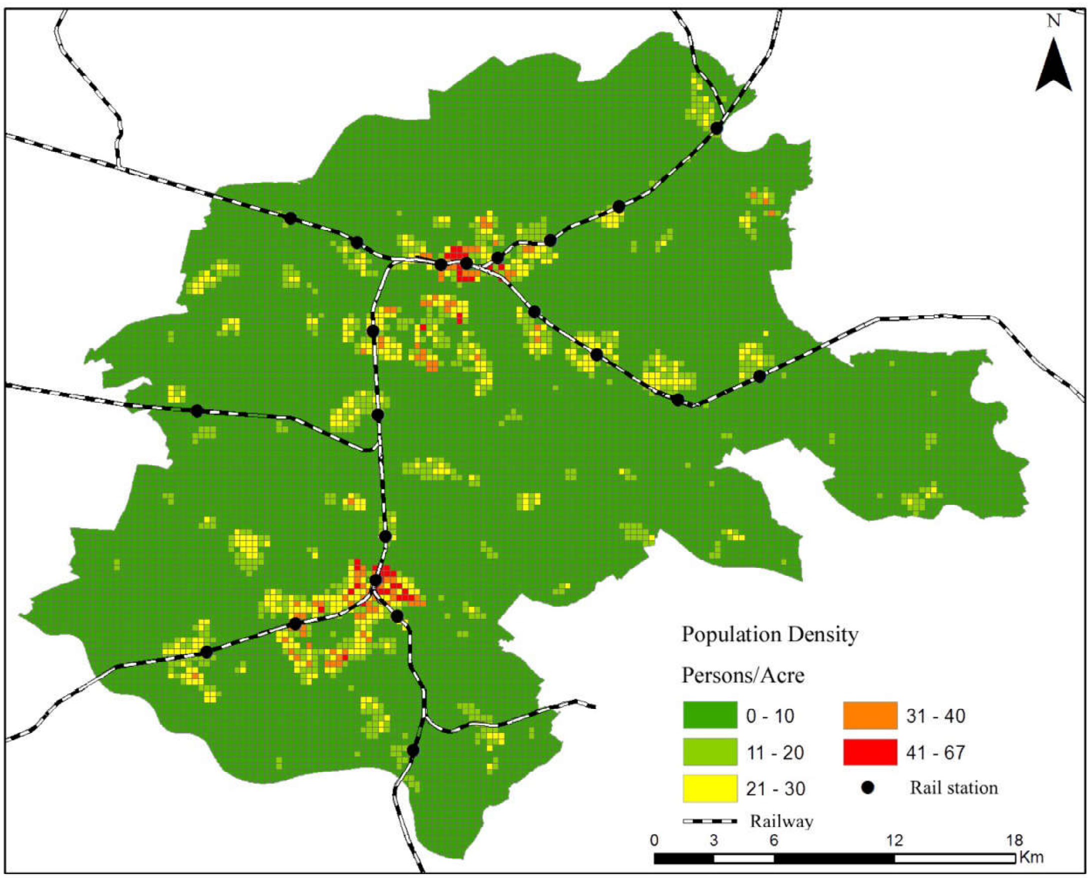
3.3 Employment Density

The employment density was calculated as number of jobs per km^2 using the similar procedure as that employed for other two density indicators. Here, all the non-residential building footprints were used for data apportionment.

3.4 Land use Diversity

This indicator is intended to measure the number of different land uses in a given area and the degree to which they are represented in that land area. Entropy method can be used to quantify the land use diversity as follows (adapted from Cervero, et al., 1997) :

Fig. 2 Population Density in the City Region



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

where,

$$Pi = \frac{Sji}{Si} \qquad (2)$$

S_i= Total area of analysis i.

S_{ji}= Total area of land use j within area of analysis i.

n=total number of land use types.

The entropy method produces an index between 0 and 1, where a value of 1 implies most balanced mix of land uses and a value of 0 indicates the presence of no or just one kind of land use. Only urban land uses such as residential, commercial, industrial, office, service, health care, education and sports were used for this calculation. However, for the measure of land use diversity, the size of a grid cell or our area of analysis is only 9 hectares which cannot accommodate a variety of land uses (Cervero, et al., 1997). A typical TOD area is covered within a comfortable walking distance which is most commonly about 500m. Thus, a window of analysis was created with a radius of 500m from the cell centroid and land use diversity was calculated for that window of analysis (Fig. 3). The land use diversity for the City Region is shown in Fig.4.

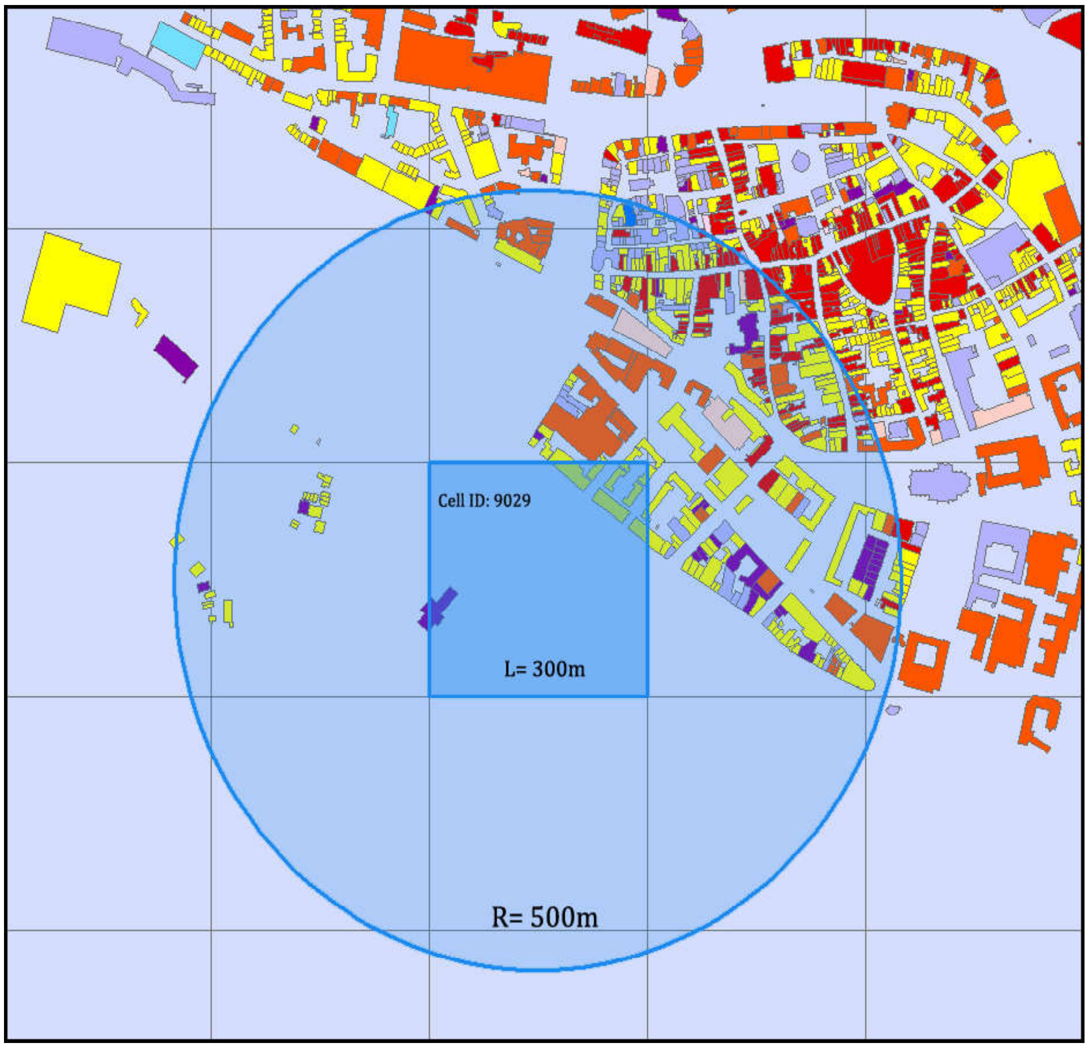
3.5 Mixedness of Land use

This indicator has been used to express the walkability and cyclability of an area. It has been discussed in literature that by adequately mixing residential land use with other land uses, people can be encouraged to walk or cycle to do their daily chores. Thus, in this indicator we measure how residential land use is mixed with other land uses using a 'mixedness index (MI)' formula as follows (adapted from Zhang, et al., 2006):

$$MI = \frac{Nc}{Nc+Nr} \qquad (3)$$

Where Nc is the area under other land uses and Nr is the area under residential land use in area of analysis. The value of this indicator is best at 0.5 because that's when residential land use is equally supported by other land uses. The results of this indicator are shown in Fig. 5.

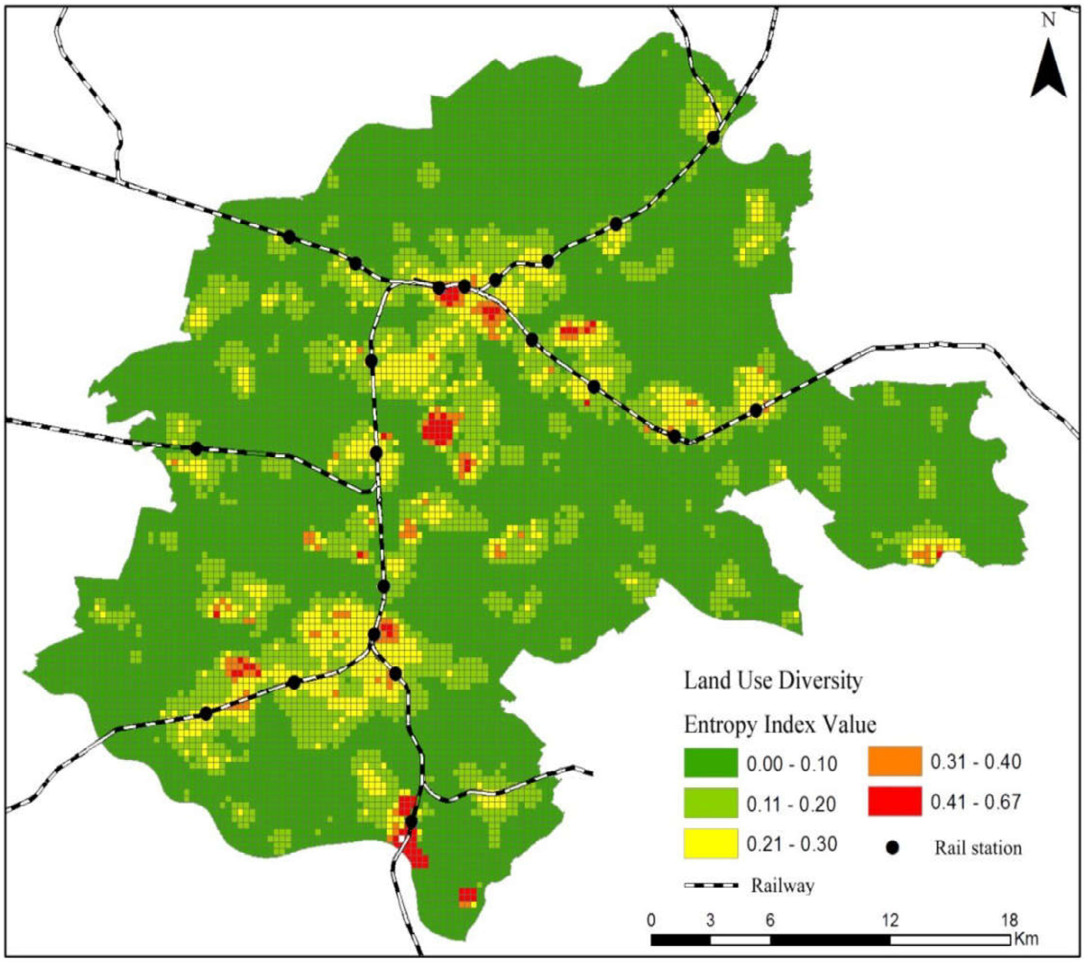
Fig. 3 Window of Analysis used for Land use Diversity Indicator



3.6 Intersection Density

The number of intersections and total length of accessible paths for walking and cycling are simple measures of walkability. An area with higher number of intersections (3-way or more) can create a pedestrian-friendly environment as people can shorten their walking distances.

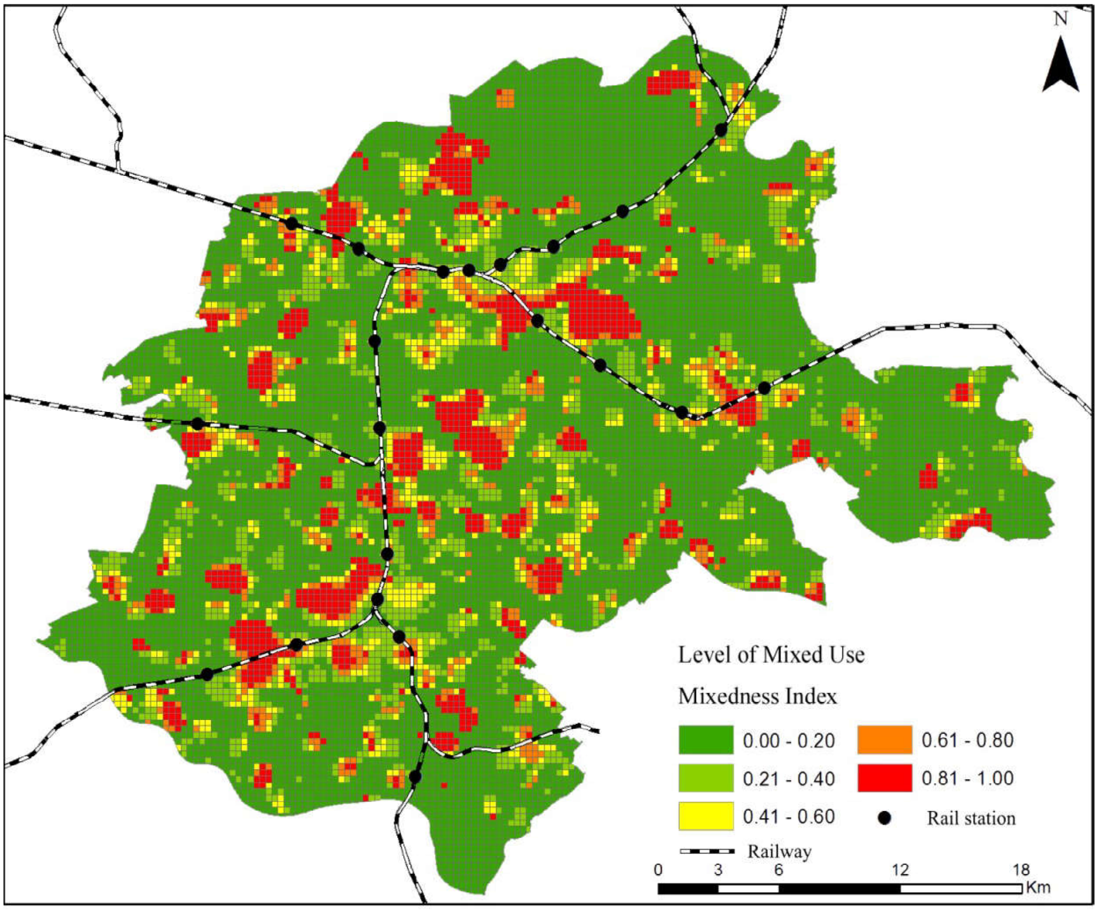
Fig. 4 Land use Diversity in the City Region



3.7 Total Length of Walkable or Cyclable Paths

Streets that are accessible to pedestrians are important for people to walk or cycle. Major roads like highways are excluded from this calculation since it is not safe to walk or cycle on such roads. The total lengths of accessible paths in each grid cell of the City Region are shown in Fig.6.

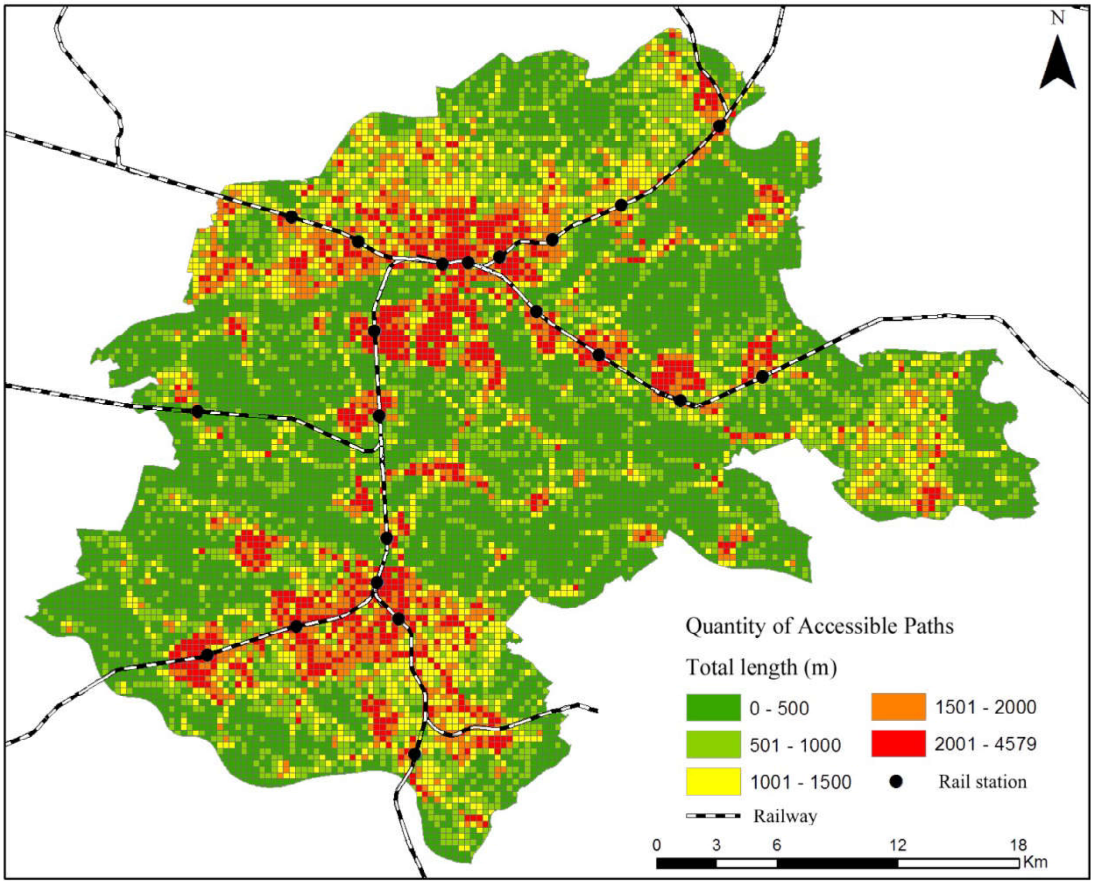
Fig. 5 Mixedness of Residential Land use with other Land uses



3.8 Business Density

The economic development of an area can be indicated by the number of business enterprises. The data on same was used from CBS and that included the business enterprises in industrial, commercial and non-commercial sectors. Using building footprints of similar nature, business density per grid cell was calculated by data apportionment method as explained in section 4.1.

Fig. 6 Availability of Paths Accessible for Walking and Cycling, in the City Region



4. SPATIAL MULTI-CRITERIA ANALYSIS (SMCA)

In SMCA, two main steps of standardisation and weighing are required and they are explained below.

4.1 Standardisation of Indicators

As mentioned before, all our indicators have different units. In order to be compared and combined we standardised the indicators such that the values of all indicators range from 0 to 1. Using the 'maximum' method, all maximum values of the indicators were set to 1 and proportionately, all other values of the indicator were reduced to a value less than 1.

There is another standardization that is required to indicate the relationship of each indicator to the final index. If an indicator is directly proportional to the index i.e. an increase in the value of an indicator increases the TOD index value, then there is a 'benefit' relationship between the two. An inverse of this relation is called 'cost'. All our indicators are directly related to the index and hence standardised using 'benefit' method, except for the 'mixedness' indicator that was standardised using a 'combination' method. Under this method, increase in the value of mixedness is beneficial to the index value till it reaches a value of 0.5 after which, it acts as a 'cost'. This was done since 0.5 is the optimal score for this indicator, indicating a balanced mix of residential with other land uses.

4.2 Weighing the Indicators

The next step in SMCA is weighing standardized indicators. Our TOD Index has four criteria and each criterion has a number of measurable indicators. The weight of each indicator is an indication of its importance to its respective criterion and the weight of each criterion indicates its importance to creation or realisation of TOD. The most commonly used method to weigh the indicators is ranking, where all criteria and their indicators are ranked in terms of their importance.

For this research, the municipal heads of the City Region were involved and in a special workshop, they were asked to weigh the indicators and criteria. Their ranks were then aggregated using the Borda Count method (Reilly, 2002) and the ranks were further converted to weights in ILWIS using the rank sum method (ITC, 2007). The final weights were then input in ILWIS along with the respective indicators' maps and a TOD index is calculated for each of the approx.12,000 grid cells. Table 1 shows the weights that were used for SMCA analysis.

5. RESULTS OF TOD INDEX

Upon conducting SMCA, the TOD index results were derived and those are shown in the Fig.7. As can be seen, higher TOD values exist around the main cities of the region and most of the region has very low TOD values. It is interesting to see that the average TOD index value for the City region is only 4.47 while the maximum stands at 0.55. The reason for an overall low TOD score is that this is an urban region that also includes large forests and rural areas engaged in agriculture activities.

Table 1: Weights for Criteria and Indicators used for SMCA

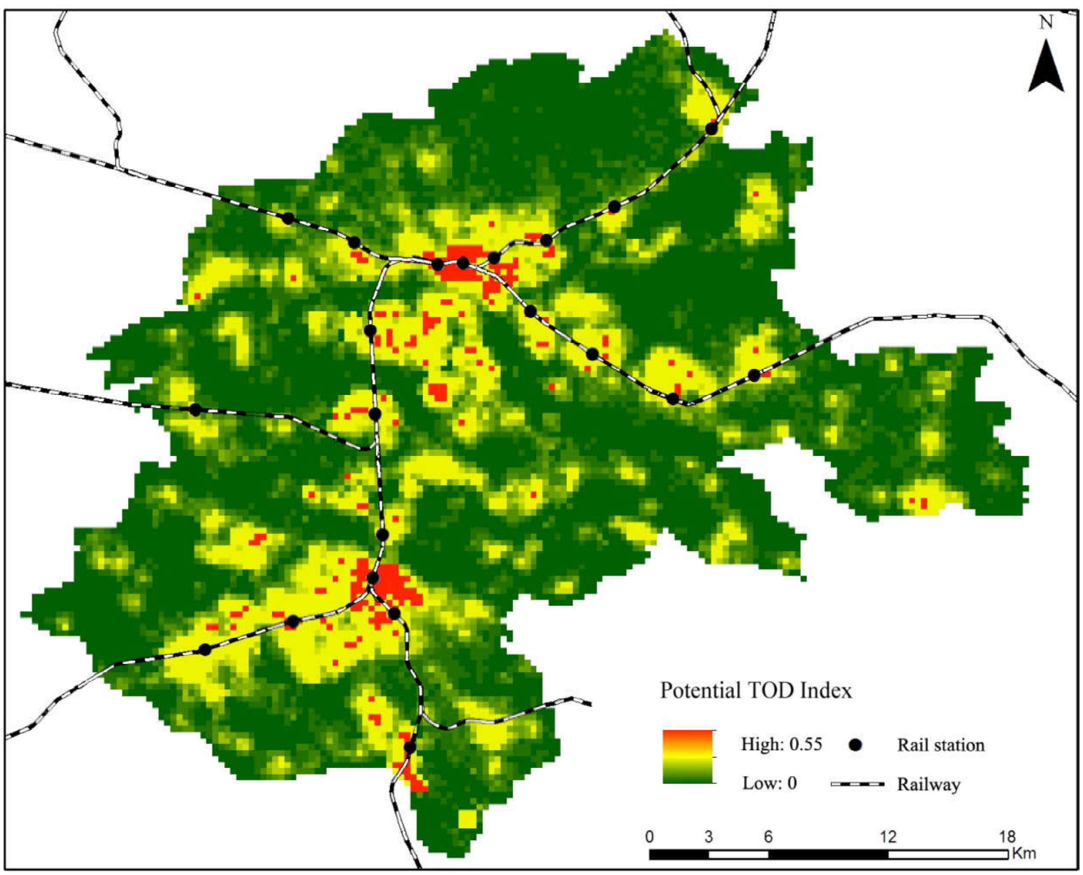
S. No.	Criteria	Weights	Indicators	Weights
1.	Area around transit node should have a minimum transit supportive density	0.3	Population density	0.5
			Commercial density	0.33
			Employment Density	0.17
2.	Land use diversity is essential for effective utilisation of transit	0.2	Land use Diversity	1.0
3.	Area around transit node should be walkable and cyclable	0.1	Mixedness of residential land use with other land uses	0.17
			Total length of walkable/cyclable paths	0.50
			Intersection density	0.33
4.	Higher economic development in the	0.4	Density of business establishments area around transit leads to higher TOD-ness	1.0

Source: Authors

Since all the indicator values have been standardised and weighted, the maximum value of the TOD index cannot go beyond 1. Also, as this research has not been carried out at any other place, we do not have reference values of what could be called a 'high-enough' TOD index value. Nonetheless, as the areas around existing stations at Arnhem and Nijmegen have highest TOD levels of about 0.55, it can be inferred that if hot spots of high TOD index values are identified, then those hot spots can be recommended for better transit connectivity. However, before the identification of hot-spots, it is required to ensure through a sensitivity analysis that our results are robust.

SMCA has become a well-established tool for solving spatial choice problems, but it has also been criticized for uncertainty present in outputs (Van Wee, 2011), Beuthe, 2002) especially because this method involves weights. There is an inherent uncertainty in the weights specified by the people that may be due to limited or imprecise information and knowledge (Malczewski, 1999). Thus, a sensitivity analysis is required to assess the robustness of the results. Thus, at an uncertainty level of 10 per cent, the results of TOD Index were assessed. The weights of each criterion were increased or decreased by 10 per cent while the weights of others were accordingly changed such that the total of weights never exceeds 1. With these changes, eight scenarios were produced with different TOD index results. It was found that in all the eight scenarios, the maximum index values remained the same and the mean value ranged from 4.32 to 4.61. These minor changes prove that our TOD index results are quite robust. In the next section, we move on to finding hot-spots of high TOD index values using spatial statistical tools.

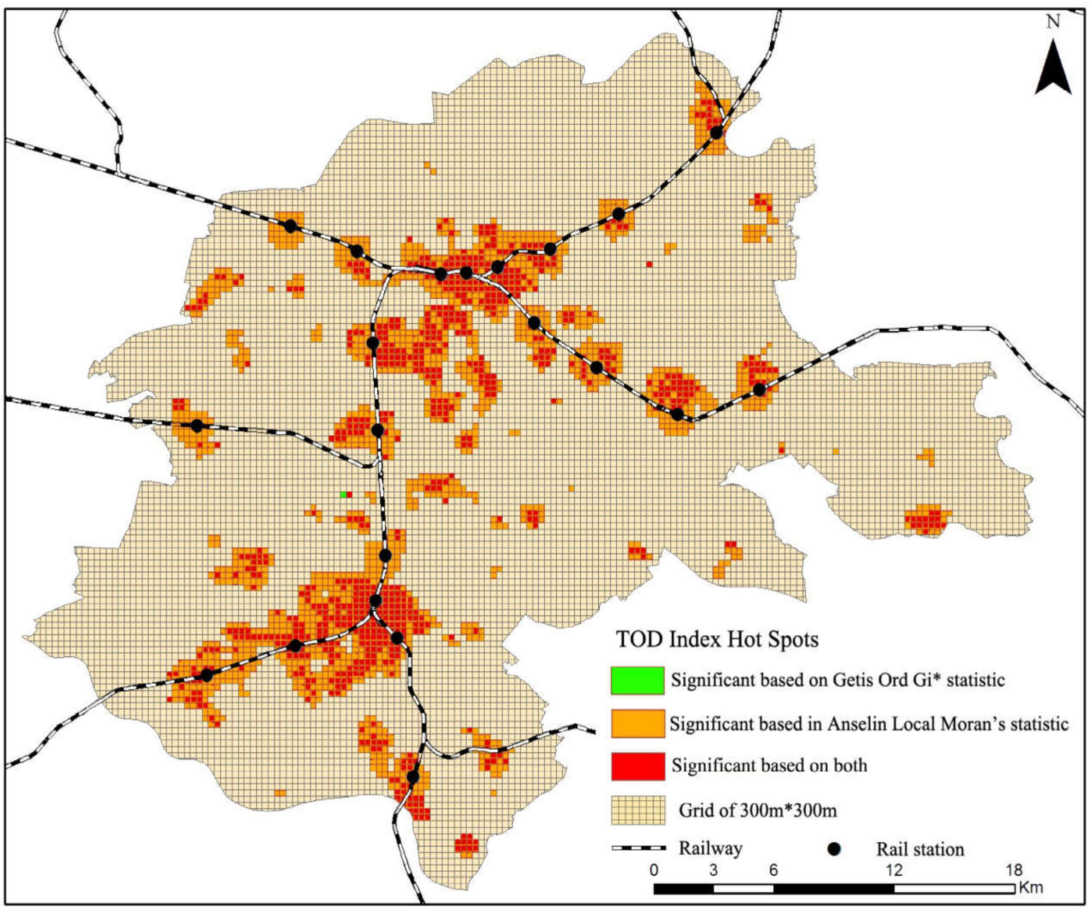
Fig. 7 TOD Index Values in the City Region



6. HOT-SPOT ANALYSIS

In order to statistically identify find the hot-spots of high TOD index values, it was necessary to examine whether such clusters of TOD index value exist or not within our City region. Thus, using Global Moran's I statistic, it was confirmed that there exist clusters of TOD index values in the City Region. Next, these clusters need to be spatially identified. The spatial statistics of Getis Ord Gi* and Anselin Local Moran's I, used in clustering or identifying hot-spots, were used to spatially locate the clusters of high TOD index values.

Fig. 8. Tod Index Hot-spots



The Getis Ord Gi* identified those cells that have high values compared to the whole region and Anselin Local Moran's I helps in identifying pockets or areas or hot spots where high index value is also surrounded with high values and constitute a hot spot when compared to region's values. To finally identify our hot-spots, we chose those areas that were identified as significant 'hot-spots' by both the statistics (Fig. 8).

Since our aim is to find those hot spots that have poor access to transit, we also measured the access to transit of all the grid cells in the City Region. The Transport for London (TfL) has a well-established method of measuring the access to their public transport system and that is called Public Transport Accessibility level (PTAL) (TfL (2010)). The method measures accessibility to transit Service Access Points (SAPs) for a Point of Interest (POI) by considering the walking speed, walking time, reliability factor and service frequency in the peak hours. The total PTAL for a POI can be calculated as a sum of accessibility (A) to different modes from that POI as follows:

$$PTAL = A_{mode1} + A_{mode2} + \ldots\ldots\ldots A_{mode\ n} \quad (4)$$

$$A_{mode\ n} = EDFmax + (0.5 * \text{All other EDFs}) \quad (5)$$

Where EDF = Equivalent Door Step Frequency to a SAP, calculated as follows:

$$EDF = 30/\text{Total access time} \quad (6)$$

and Total Access time = Walking time + Average waiting time (7)

For our case, the cell centroids were taken as POIs, the BRT stops and train stations were taken as Service Access Points (SAPs), the data on service frequency was collected from the service providers' websites and PTAL was calculated was each grid cell. It is worth mentioning that unlike London, on which this system has been based, we did not study the regular bus systems. That is because for successful TOD, transit must be high quality, dependable and competitive when compared to private modes of transport like cars. Newman (2009), Hale, et al. (2006), Newman, et al. (2007) and others have mentioned that rail based transit and Bus Rapid Transit (BRT) systems have competitive edge in terms of capacity, speeds and dependability as compared to cars. Regular buses have high capacities but can be very slow and can be stuck in traffic in peak hours, thereby reducing its level of service. Thus, regular buses were not studied for PTAL measurements. This also affected the total scores of PTAL for the region since the maximum score achieved for the City Region was only 12.5. For a big city like London, a PTAL score of 40 or above is expected while considering all modes of transit (TfL, 2010). Since our City Region, with a mix of urban and rural elements, cannot be compared with a high density urbanised city like London, it is not prudent to follow the guidelines mentioned in TfL (2010) regarding which score is low and which is high. Thus, we prescribed our own reference range of a score of 2.5 as 'poor' access to transit. Thus, a cell that belongs to a hot-spot and also has a PTAL score of 2.5 or less, is identified to be that area where transit access needs to be improved. The Fig.9 shows those hot spots that need better transit access.

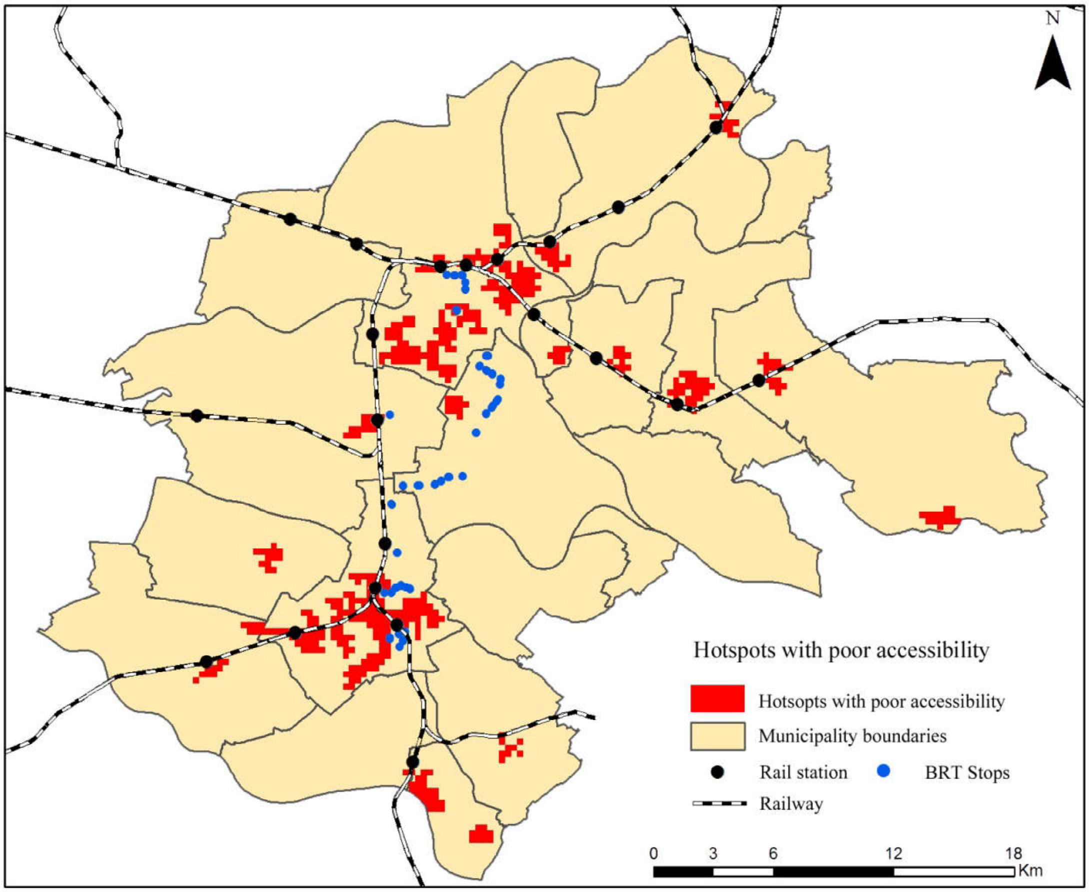
The City Region officials can consider improving their access to transit by either improving the current frequency of service or extending BRT lines to these areas.

7. CONCLUSIONS AND RECOMMENDATIONS

Using the TOD index, we have been able to measure the level to which the TOD characteristics are present at various locations in the City region. It has also helped in identifying hot-spots of high TOD index values that are expected to be transit oriented. Supplementing this with PTAL has helped to shortlist those hot spots that need better transit connectivity. It is recommended that a high quality transit service like train or BRT may be extended to these areas. Since train- based solutions can be very costly, BRT is preferred. These results can be further followed-up with detailed demand assessment, technical feasibility analysis, financial – economic feasibility analyses and others.

Our methodology to measure TOD is very comprehensive since it allows for multiple indicators to be included for measurement and they need not be only spatial or non-spatial in nature. It is also transparent and can be easily adapted/ adopted for other case studies. SMCA also allows for reflection of the planning priorities by involving the stakeholders or decision makers in the weighing exercise.

Fig. 9 Hot-spots with Poor Transit Accessibility



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