# DEVELOPMENT AND IMPLEMENTATION OF A TRANSIT ORIENTED DEVELOPMENT (TOD) INDEX AROUND THE CURRENT TRANSIT NODES

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February, 2014

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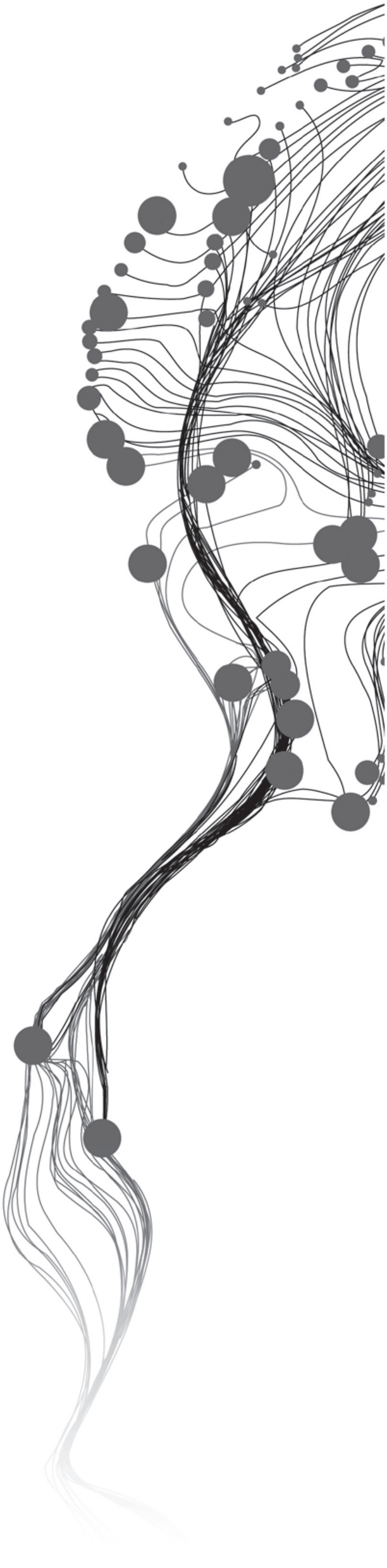

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Enschede, The Netherlands, February, 2014

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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# ABSTRACT

Nowadays, cities were confronted with serious problems e.g. traffic congestion, air pollution, lack of public space, urban sprawl, and segregation of community. *Transit Oriented Development (TOD)* is believed as one promising concept to overcome the urban problems through encouraging land use and transport integration. However, different interpretations of the concept lead to difficulties of conducting TOD planning. This study believed that TOD planning should be preceded by understanding the existing condition through measurement of TOD level.

Transit node plays central role in TOD. Therefore, the measurement of TOD level around the existing nodes is inevitable. The core area of TOD was defined as *800 meters* (10 minutes) walking distance. This study focused on this area of walking distance from transit nodes.

This study measured TOD level in city region Arnhem and Nijmegen, by constructing TOD index for 21 transit nodes in the region. Indicators and criteria were identified based on important aspects of TOD. There are 25 indicators identified and only 18 indicators were chosen due to the availability of data. The indicators were divided into *spatial* and *non-spatial indicators*. Geographic Information System (GIS) platform was used to quantify all of spatial indicators. To construct composite index, Multi Criteria Evaluation (MCE) was conducted in ILWIS for all of the criteria and indicators.

Stakeholder participation was employed during the process in MCE. The weights of each indicator and criterion were decided based on stakeholder preferences. The weights play significant role towards the final index. Therefore, the proper method should be used when deriving stakeholder preferences.

The result of this study is aggregated index for 21 transit nodes in city region Arnhem and Nijmegen. Composition of TOD index for each transit node was examined to identify potential improvement for all the transit nodes. TOD index was found useful to support the process of TOD planning in study area. In the end, sensitivity analysis was performed to examine the effect of slight changes in criteria weights towards TOD index.

Keywords: TOD, TOD Index, Transit nodes, Indicators, Criteria, GIS, MCE, Stakeholder, Sensitivity Analysis

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Azhari Lukman
February, 2014

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| | |
|---|---|
| LUTI | Land Use and Transport Integration |
| TOD | Transit Oriented Development |
| GIS | Geographic Information System |
| MCE | Multi Criteria Evaluation |
| SAN | Stadregio (City Region) Arnhem and Nijmegen |
| CBS | *Centraal Bureau voor de Statistiek* (Central Agency for Statistic in The Netherlands) |
| OSM | Open Street Map |
| IPCA | Impedance Pedestrian Catchment Areas |
| NS | Nederlanse Spoorwegen (The largest train service in The Netherlands) |

# 1. INTRODUCTION

## 1.1. Background and Justification

### 1.1.1. Background

Nowadays, many cities experience urban problems because of a lack of integration between land use and transportation policy. Some of these issues specifically are traffic congestion, air pollution, noise pollution, traffic accidents, inequitable access to transport and services, unreliable public transport, overcrowding, urban sprawl, and segregation of community (Alqhatani et al., 2012; Curtis, 2005; Jonsson, 2008). Therefore, it is necessary to encourage Land Use and Transport Integration (LUTI) to ensure the sustainability of the cities.

The concept of land use and transport integration has since long been realized by planners as an essential component of cities development. Curtis (2005) put LUTI as an ubiquitous phrase in planning and it has been part of planning ideology for decades. However, the concept of LUTI must be carefully formulated to gain the most benefit of it. Preston (2010) argues that integration has been proven so difficult to achieve, because of the failure to define the concept and the failure to operationalize the concept. Various definitions of the concept can be found in literature. Curtis (2005) pointed out that a definition of LUTI consists of four aspects that must be addressed equally as they are complementary, namely physical, spatial, behavioural, and institutional characteristics. Some other literatures introduced accessibility measures as the main framework to achieve land use and transport integration (Bertolini et al., 2005; Halden, 2002).

As frequently-used concept, accessibility suffers the same dispute as LUTI. This concept has been commonly used in a number of fields such as urban planning, transport planning, and transport geography (Zuidgeest, 2005). There is no common consensus related to its definition and formulation (Vandenbulcke et al., 2009). Accessibility is generally described as the ease with which specific activities can be reached from a certain place using a certain mode of transport (Morris et al., 1979; Vandenbulcke et al., 2009). Handy et al. (1997) proposed that accessibility can be determined based on the spatial distribution of potential destinations, the ease of reaching each destination, along with the magnitude, quality, and character of the main activities.

Another important concept to achieve land use and transport integration is Transit Oriented Development (TOD). Curtis et al. (2009) defined TOD as straightforward concept to "concentrate a mix of moderately dense and pedestrian friendly environment around transit stations to promote transit riding, increased walk and bicycle travel, and other alternatives to the use of private cars". TOD is closely related to the accessibility concept. TOD poses an important role to increase overall accessibility in the area. In addition to promoting mode shift from car to transit, TOD increases accessibility and transportation options through land use clustering and mix, and non-motorized transportation improvements (VTPI, 2012). Moreover, Renne (2008) revealed one of important factors in TOD, is high level of local accessibility that differentiates this concept with the Transit Adjacent Development (TAD), which is conventional, automobile-oriented development located near transit stations.

TOD has gained much attention from the planners since many years. The concept provides a solution to the urban transport problems mentioned earlier by incorporating the change in land use pattern (Ratner et al., 2013). The basic idea of TOD is concentrating urban development around transit nodes with particular characteristics such as relatively high density building, compact and mixed development, and efficient public transportation services, along with a pedestrian friendly environment (Cervero et al., 2008; Curtis et al., 2009; Knowles, 2012; Loo et al., 2010). TOD is not just about the development near the transit, but further it increases location efficiency for non-motorized mobility, boosts transit ridership, provides a rich mix of housing, jobs, shops and recreational facilities, provides value for the public and private sectors, and creates a sense of community (CTOD, 2011). The concept aims to reduce car use and to promote the use of public transit and human-powered transportation modes within areas of walking distance from transit centres (Wey et al., 2013).

The popularity of the TOD concept is not without a reason. The benefits of TOD are apparent in several cases, e.g. to contribute in reshaping urban form in Denver (Ratner et al., 2013), to increase job accessibility in Shanghai (Cervero et al., 2008) and to increase property values and commercial activity, which can lead to higher tax revenue (VTPI, 2012). Furthermore, research by CTOD (2011) shows that TOD can be an important affordability strategy by introducing affordability as combined costs for housing and transportation. Mixed-housing development around a transit system provides people with more housing and transportation choices, so they can enjoy affordable, convenient, and active lives (CTOD, 2011). Similarly, the experience of implementing TOD for 60 years in new town Orestad, exhibits important and successful achievements of contemporary planned sustainable TOD which helps Copenhagen to increase its international competitiveness, increase Central Business District (CBD)'s accessibility, attract major commuter flows from much wider area, engage the residents to choose public transport or cycling instead of private car, create thousands of new jobs, and provide new residential districts with attractive natural environment and very accessible from CBD (Knowles, 2012).

### 1.1.2. Justification

Given the increasing popularity of TOD, there are attempts to measure and evaluate it (Curtis et al., 2009; Renne, 2007). Measuring the TOD level of an area is an important task to evaluate the success of TOD plans (Singh et al., 2012). More importantly, measurement of TOD is essential for TOD planning. TOD level reflects the degree of existing condition towards the ideal conditions based on the TOD concept. As the planning process requires the knowledge of existing situation, therefore, the understanding of current TOD level will help us to plan how to improve the TOD level. Moreover, with the aid of multi-criteria assessment, it can contribute to more transparent process of measurement. It reveals explicitly the contribution of each criteria or indicators to the TOD level, which will ease the process of TOD planning. TOD level is quantified as *TOD index* in this research.

Singh et al. (2012) revealed that there are no current methods which quantitatively measure the TOD level, and even though there are proposed indicators to quantitatively evaluate and measure the TOD level, they have not been used comprehensively. Therefore, Singh et al. (2012) proposed a framework to quantitatively measure the TOD index of a location. The result can be used to identify specific planning actions or recommendation required to improve the TOD level of an area. Fard (2013) adopted the framework to measure existing TOD levels using a GIS-based spatial model as an analytical measurement tool.

Spatial platforms such as GIS and Multi Criteria Evaluation (MCE) tool are essential to build a TOD index since land use and transport mostly deal with spatial data and analysis. Fard (2013) stated that developing a GIS based geo-processing model is inevitable, in order to perform series of spatial analytical operations. Then, using MCE, TOD level can be quantitatively measured and visualized as TOD index based on the defined indicators. Furthermore, the measurement of TOD levels can be enhanced by involving the stakeholders in the process. MCE provides a nice platform to accommodate the stakeholder participation. Stakeholders can be involved in assigning the weights of TOD indicators in MCE platform.

Fard (2013) developed a potential TOD index which mainly focused on the calculation of index for each location in a region. The index was applied on the whole areas in the region, regardless of the areas had transit access or not. Hence, this work did not incorporate elements of the transit system in detail since these elements only exists at specific location.

This research will focus on the measurement of TOD levels around the existing transit nodes in the city region. TOD levels will be measured as TOD index. Various indicators representing the main aspects of TOD will be used to construct this TOD index. In addition to the indicators related to the built environment around the transit nodes, some indicators related to the element of transit system will be incorporated as well. Hence, number of indicators used in this research will be many more than the indicators used by Fard (2013).

Most of the TOD studies deal with the area around the existing transit nodes. The built environments around the walking limit were measured in terms of the TOD aspects such as land use diversity, density, pedestrian access and amenities, walkability and other development aspects that encourage walking environment and reduce the use of motorized transport. Indeed, the factors specific to the transit node e.g. transit utilization, transit quality, connections to other nodes, and parking, also play important role for the TOD area. It is essential to understand current condition of existing transit nodes in order to formulate better plan for TOD planning. Every station in the region could have different level of TOD level with various levels of the TOD aspects as well. Consequently, the planning actions required for each station will also be unique one another.

## 1.2. Research Problems

There is no standard or universal definition of TOD. It was described diversely by different researchers and practitioners as they have different perspectives on the concept. The definition of TOD changes as the intended aims of TOD change (Singh et al., 2012). Consequently, the ways of assessing and evaluating TOD are also diverse. Cervero et al. (1997) is widely known by his 3D concept (Density, Diversity, and Design) which is considered as an important aspects to evaluate TOD planning. Similarly, Calthorpe (1993) focuses on physical characteristics especially the walkable environment. On the other hand, Belzer et al. (2002) criticized that most of TOD definitions emphasize more on the physical and design aspects and they proposed a set of six performance criteria e.g. location efficiency, value recapture, liveability, financial returns, choice of lifestyle, and efficient land use pattern.

Newman (2009) noted the importance of the quality of transit system, so it can compete with private transport. Unfortunately, in most cases, TOD planning does not incorporate service levels of the transit system. Most of the studies about TOD focused only on the built environment around the station. The transit quality, however, should be incorporated as well because it dictates the usability of the public transport. Good and comprehensive measurement of TOD needs to incorporate the development of the area around the transit, along with the transit quality proportionally. Renne (2007) indicates nine the most important indicators for TOD evaluation, and three of these indicators (transit ridership, quality of intermodal connections and parking configuration) are mainly representing transit quality. Moreover, Sung et al. (2011) and Loo et al. (2010) found there is a relationship between TOD planning factor and transit ridership.

These studies and many other studies related to the assessment of TOD, have been trying to evaluate the TOD planning, but none have gone further into explicitly trying to measure the level of TOD quantitatively in form of an index. Most of the studies focused mainly on the evaluation of TOD plans (Singh et al., 2012). Therefore, the results are incomparable, less comprehensive, and unable to cover the whole aspects proportionally. Some studies have identified the main indicators to measure the TOD level, but these indicators are not established in operational manner yet. Therefore, there is a need to measure the level of TOD in the form of an index, in order to formulate better TOD plans.

Hence, it is essential to measure the TOD level comprehensively covering the main aspects such as the development aspects around the transit nodes and the quality of the transit nodes. The research problem in this study is described as the "*Lack of spatially explicit tools to comprehensively measure the TOD levels around the current transit nodes in an area*".

## 1.3. Research Aim, Objectives, and Questions

### 1.3.1. Aim

"To develop and implement a GIS-based model for measuring the TOD levels around the current transit nodes using a TOD index, and to identify the areas where the TOD levels can be improved"

### 1.3.2. Objectives

1. To identify the indicators for measuring the TOD index around the current transit nodes (rail station), using the framework provided by Singh et al. (2012).
2. To develop GIS based model for quantifying the TOD indicators.
3. To incorporate stakeholder preferences in the process of calculating the TOD index.
4. To construct a composite TOD index using Multi-Criteria Evaluation (MCE).
5. To identify aspects which need to be improved around the transit nodes based on the TOD index values.

### 1.3.3. Research Questions

The research questions are formulated on the basis of objectives presented above.

1. **To identify the indicators for measuring the TOD index around the current transit nodes (rail station), using the framework provided by Singh et al. (2012).**
    1.1. What are the main indicators to measure the TOD index around the current transit nodes comprehensively?
    1.2. How important is each indicator for the attainment of TOD?
    1.3. Can new indicators be introduced in addition to the indicators identified by Singh (2013)?
    1.4. Should any indicators be removed or modified from the indicators identified by Singh (2013)?

2. **To develop GIS based model for quantifying the TOD indicators.**
    2.1. What can be defined as a walk-able limit from a train station?
    2.2. How can the buffer be created around train station using the walkable limit?
    2.3. How to measure/quantify each of the chosen indicators?
    2.4. How to accommodate the chosen indicators into GIS model?
    2.5. What data are required to calculate the chosen indicators?

3. **To incorporate stakeholder preferences in the process of constructing the TOD index.**
   3.1. How to present the TOD criteria and indicators in a clear and 'easy to understand' manner?
   3.2. Which methods of weighting that are more appropriate to be applied for the stakeholders?
   3.3. How is the relative importance of indicators (weights) based on the stakeholders' viewpoint?

4. **To construct a composite TOD index using Multi-Criteria Evaluation (MCE).**
   4.1. How to standardize indicators' values?
   4.2. How to visualize the quantified TOD index?
   4.3. How sensitive is the result of TOD index towards the certain change in weights?

5. **To identify aspects which need to be improved around the transit nodes based on the TOD index values.**
   5.1. Which stations have higher index and which ones have lower TOD index?
   5.2. What aspects that can be improved at each station based on the composition of TOD index?
   5.3. Which stations have more potential for improvement on the basis of the TOD indicators?
   5.4. What are improvements per station that can be suggested to the stakeholders?

### 1.4. Conceptual Framework

The conceptual framework of this research is presented in the Figure 1-1.

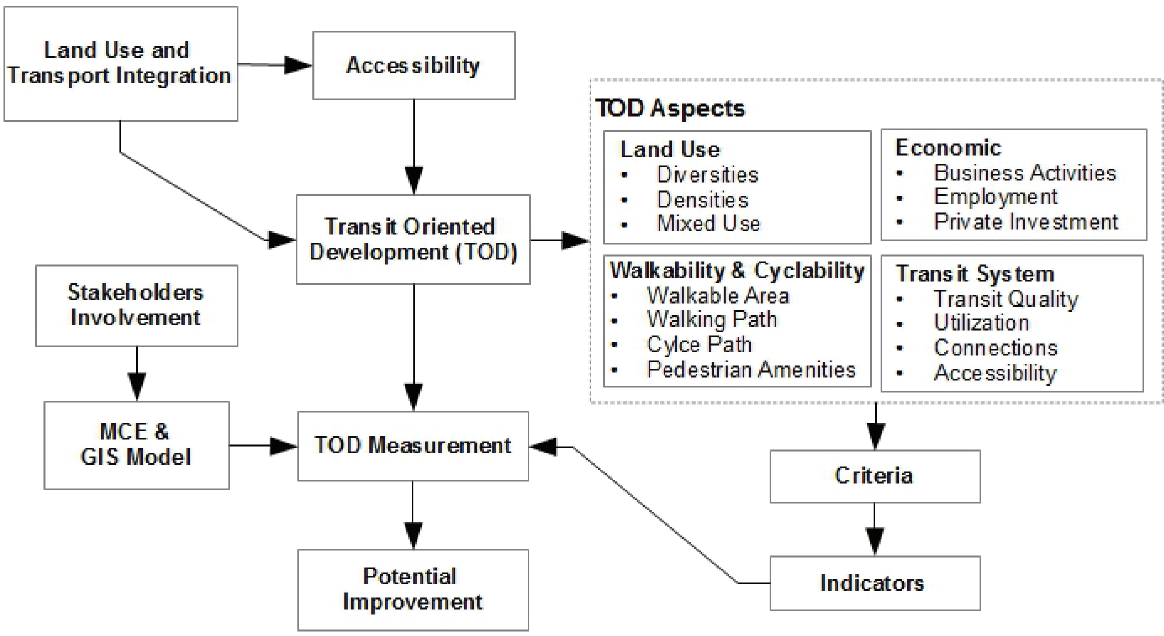


Figure 1-1 Conceptual Framework

The research took off with the idea of land use and transport integration which has significant influence on the sustainability of the cities. In addition to that, the concern towards accessibility in transportation field gains much more attention compared to the focus merely on mobility. It was established on the basis of many researches that the accessibility concept does incorporate land use aspects and, it is essential in land use and transport integration (Bertolini et al., 2005; Curtis, 2005; Preston, 2010).

Meanwhile, the promising results of Transit Oriented Development (TOD) plans are evident in many cases (Cervero, 1996; Duncan, 2011; Knowles, 2012; Loo et al., 2010; Ratner et al., 2013). This prominent concept is believed as one of the best way to achieve land use and transport integration. Moreover, TOD is also claimed capable of increasing the accessibility around the transit (VTPI, 2012).

TOD mainly focus on the development area around transit nodes (station) that can encourage people to walk, use non-motorized transport/cycling, use public transit, and reduce the use of private cars. Therefore, the availability of networks that support the movement of pedestrians and cyclists, along with their safety and comfort, are important parts of the TOD plan. Moreover, the densities and the diversity of land uses in the area also affect the TOD level in certain way. Cervero et al. (1997) postulated that in case of non-work trips, more compact settings of residential with neighbourhood retail and pleasant walking environment are inducing more travel by foot or bicycle and short-hop transit trips, while in case of work trips, pedestrian-friendly environments and the presence of convenience stores near residences are expected to induce commute trips via transit and non-motorized modes. Last but not least, the transit system itself also poses an important role to complement the success of the TOD plan. Sung et al. (2011) implied that the availability, quality, and quantity of transit system are essential aspects of TOD plan and have strong relationship with the transit ridership.

Therefore, given the criteria presented above, this study tried to measure TOD level through constructing an index that can comprehensively represent the TOD level of the area around the transit nodes. It was argued that currently there is no effort of measuring the TOD index explicitly (Singh et al., 2012). The index was calculated based on the indicators of TOD level. Each indicator was chosen based on the criteria whereas these criteria were derived based on the important aspects representing TOD.

GIS Modelling and Multi Criteria Evaluation (MCE) were used as tools to quantify the TOD level. The 'taste' of stakeholder participation was also engaged during the weighting in MCE. MCE, together with GIS platform, is a powerful tool to capture each of stakeholder preferences and to compare the different results on the basis of different weights. This advantage helped us in analysing how different viewpoints of stakeholder will affect the TOD index produced. Moreover, the distinct composition of single index also helped us in identifying which nodes should be prioritized to be improved, and which aspect of TOD in the certain station has more potential to be improved in the future.

## 1.5. Research Design

### 1.5.1. Methods

The methods were structured on the basis of research objectives and research question formulated previously. This part presents the summary of the methods, while more detailed methodology will be explained in Chapter 3 and Chapter 4 of this document. It starts with Table 1-1 that shows how the research questions were derived from each objective, and it also shows the method used to answer each of the research questions. Then, the operational plan is presented in Figure 1-2.

Table 1-1 Research Objectives, Research Questions and Methods

| Objectives | Questions | Methods |
|---|---|---|
| **To identify the indicators for measuring the TOD index around the current transit nodes (rail station), using the framework provided by (Singh et al., 2012).** | What are the main indicators to measure the TOD index around the current transit nodes comprehensively? | Literature review |
| | How important is each indicator for the attainment of TOD? | Literature review |
| | Can new indicators be introduced in addition to the indicators identified by Singh (2013)? | Literature review |
| | Should any indicators be removed or modified from the list identified by Singh (2013)? | Literature review |
| **To develop GIS based model for quantifying the TOD indicators.** | What can be defined as a walk-able limit from a train station? | Literature review |
| | How can the buffer be created around train station using the walkable limit? | Literature review |
| | How to measure/quantify each of the chosen indicators? | Literature review, statistical measure, spatial analysis and GIS modelling, field visit |
| | How to accommodate the chosen indicators into GIS model? | Literature review, spatial analysis, GIS Modelling |
| | What data are required to calculate the chosen indicators? | Literature review |
| **To incorporate stakeholder preferences in the process of constructing the TOD index.** | How to present the TOD criteria and indicators in a clear and 'easy to understand' manner? | Literature review |
| | Which methods of weighting that are more appropriate to be applied for the stakeholders? | Literature review, MCE (direct, pairwise, or rank) |
| | How is the relative importance of indicators (weights) based on the stakeholders' viewpoint? | Workshop[1] |
| **To construct a composite TOD index using Multi-Criteria Evaluation (MCE).** | How to standardize indicators' values? | Literature review |
| | How to visualize the quantified TOD index? | Literature review |
| | How sensitive is the result of TOD index towards the certain change in weights? | MCE, Sensitivity Analysis |
| **To identify aspects which need to be improved in the transit nodes based on the TOD index composed.** | Which stations have lower index and which ones have higher TOD index? | MCE |
| | What aspects that can be improved from each station based on the composition of TOD index? | MCE |
| | Which stations have more potential for improvement on the basis of the TOD indicators? | MCE |
| | What are improvements per station that can be suggested to the stakeholders? | MCE |

[1] Workshop is not part of this study. This study only used the result of workshop conducted by Singh (2013) who is working on related topic.

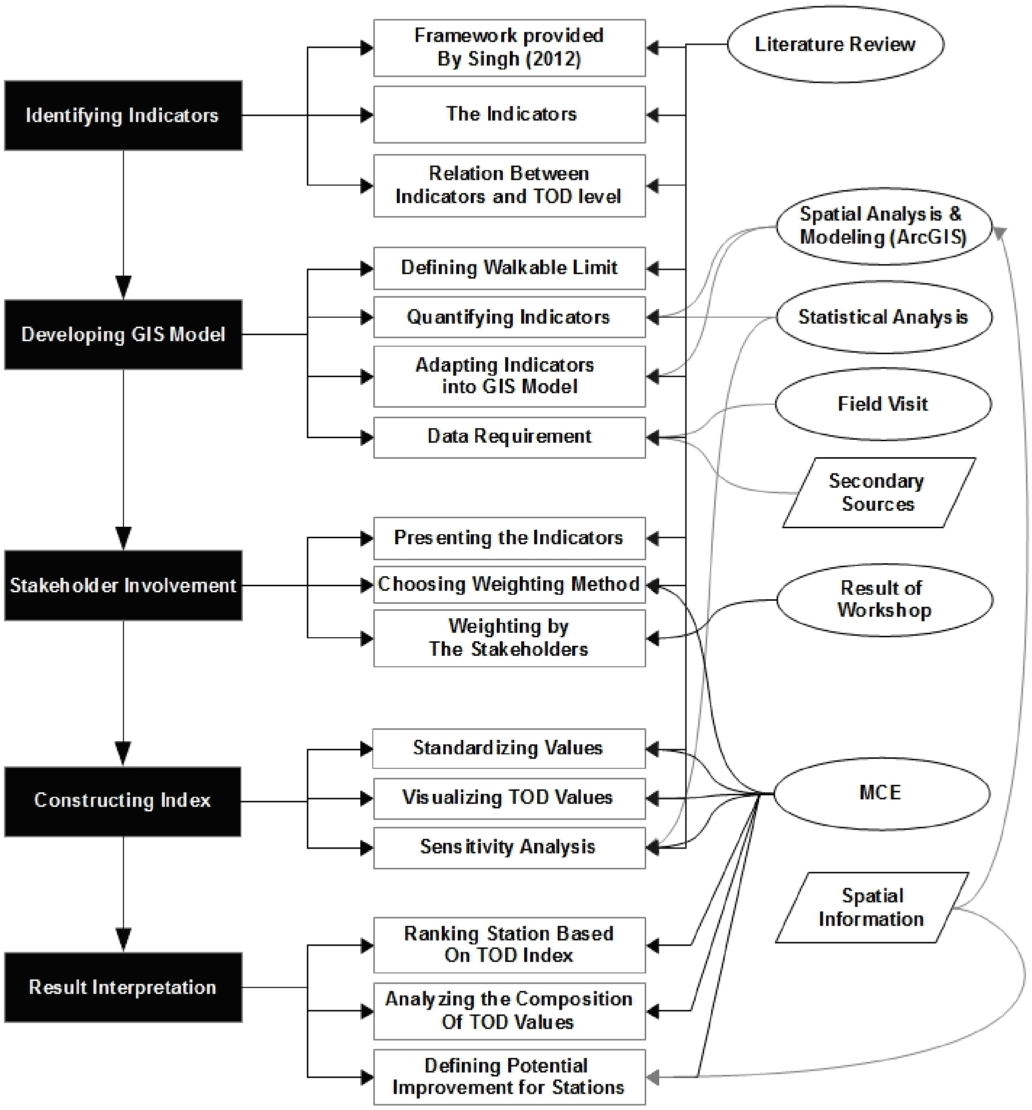


Figure 1-2 Operational Plan

#### 1.5.1.1. Identification of Criteria and Indicators

Identification of criteria and indicators plays crucial part at the initial stage of this research. It dictates the strength and the precision of TOD index in representing the TOD level. Hence, thorough and careful analysis was employed at this stage. The criteria and indicators were determined on the basis of careful literature review on the previous TOD studies. As a starting point, the criteria and indicators was derived with the aid of framework provided by Singh et al. (2012), and the list of criteria and indicators suggested by Singh (2013). The list of indicators suggested by Singh (2013) can be seen in APPENDIX A.

Identifying criteria and indicators for TOD index was based on the *top-down* approach. It started from defining what is TOD, and what aspects that are representing the TOD. Then, the aspects were translated into *criteria* and *hypotheses* which later were broken down into *indicators*. There are two list of indicators produced in this research. The first list is the list of *ideal indicators* based on the literature review and the second list is the list of *selected indicators* based on the availability and the significance of the data.

#### 1.5.1.2. Developing a GIS Based Model

Basically, there are two types of indicators: *spatial* and *non-spatial* indicators. Spatial indicators required spatial analysis of the spatial components around the transit nodes. The calculation of these components is limited by the area of walking distance around the transit nodes. This study used buffer of 800 meters (a half mile) based on the suggestion of SAN authority. Each value of spatial indicator was aggregated as one value for each station. On the other hand, non-spatial indicators did not require any spatial analysis. Most of these were derived as direct attribute value of the station. Some of these also required complex calculation without involving spatial analysis.

Spatial indicators were calculated using GIS platform. As the initial part of the quantification, the data were prepared and reclassified. Then, various methods were applied to calculate the indicators such as data apportion for non-coterminous polygon, entropy formula, and network analysis. Several GIS model were created to ease the process of calculation, especially for the particular process that had to be repeated several times. Within the model, python scripting was also used to conduct special calculation such as entropy that cannot be conducted using available GIS tools.

#### 1.5.1.3. Deriving Stakeholder Preferences

Stakeholder involvement has been a prominent procedure in the planning these days. It is believed as one way to encourage the bottom-up planning by engaging participation from the community. Similar as planning in general, the implementation of TOD planning also relies largely on the legitimacy of the plan which can be achieved through stakeholder participation.

In this study, stakeholder involvement was represented at the stage of determining weight of each indicator and criteria for the construction of TOD index. The weights were derived from Stakeholder workshop. The workshop was not part of this research. It was held by Singh (2013) who worked on the same topic as this research. Among the methods of weighing available (direct assignment, pairwise and ranking), the ranking method was chosen[2]. It was decided on the basis of stakeholder comforts, time efficient and objective accomplishment.

Based on Belzer et al. (2002), the key stakeholders in TOD planning are municipal staff, transit agency, community development groups, developers, and academic researchers. However, in this research, the weights were only derived from government representatives at municipality level. The workshop was only able to incorporate these actors.

Given the number of criteria and indicators to be weighted, the weights are quite prone to uncertainty. For instance, if another workshop is conducted the second with the same stakeholder as previous workshop, there is a possibility of getting slightly different combination of weights. Therefore it is also important to perform the sensitivity analysis in order to examine the effect of slight change of weights towards the final TOD index.

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[2] Initially, the pairwise method was intended to be used. However, the internal experiment showed that this method caused boredom, fatigue and lack of interest among the respondents. Hence the ranking method was used instead.

#### 1.5.1.4. Constructing Composite TOD Index

Developing the index was conducted with the aid Multi Criteria Evaluation (MCE) tool. MCE is known well as an effective tool to manage and combine the variables and indicators into one single composite index. Moreover, MCE platform also has ability to incorporate stakeholder preferences in terms of weighing effectively and efficiently.

The common pattern in MCE is started by defining the alternatives to be ranked, followed by identifying the criteria, assigning the weights, choosing the proper standardization, and constructing the final values (Convertino et al., 2013; Iojă et al., 2013). In this study, after the value of each indicator has been produced, the first thing necessary for MCE is to standardize the indicator values. Each of indicators has to be standardized properly based on its contribution towards TOD. The influence of indicators towards TOD value should be defined whether it is a benefit, cost or combination of both. Then, the next step involved choosing from the standardization methods available such as interval, maximum, goal, and curve.

As indicated in the previous part, the number of criteria and indicators included in this research gives certain degree of uncertainty in terms of the weights. Therefore, sensitivity analysis was performed to test the robustness of the methods used. The weights were changed at certain degree to examine their effects towards the final TOD index.

#### 1.5.1.5. Interpretation of the TOD Index

MCE provides transparency of composition value in the TOD index. Therefore, in addition to the calculation of index value for each station, it also allows us to examine the contribution of each aspect (criteria or indicators) to the aggregated index. These conditions open up wide range of opportunities to identify specific potential improvements for the transit nodes.

To examine and interpret the result of MCE properly, it is essential to find the suitable visualization. Given the amount of criteria and indicators used, the radar chart can provide better representation about the contribution of each indicators or criteria towards the TOD final index.

### 1.5.2. Study Area

Stadsregio Arnhem-Nijmegen (SAN) is a city region that consists of 20 municipalities. Two municipalities, Arnhem and Nijmegen, are the two most well-known cities in the region. All except one municipality are part of the province of Gelderland. One municipality, Mook en Middelaar is part of the province of Limburg. Figure 1-3 shows the map of study area.

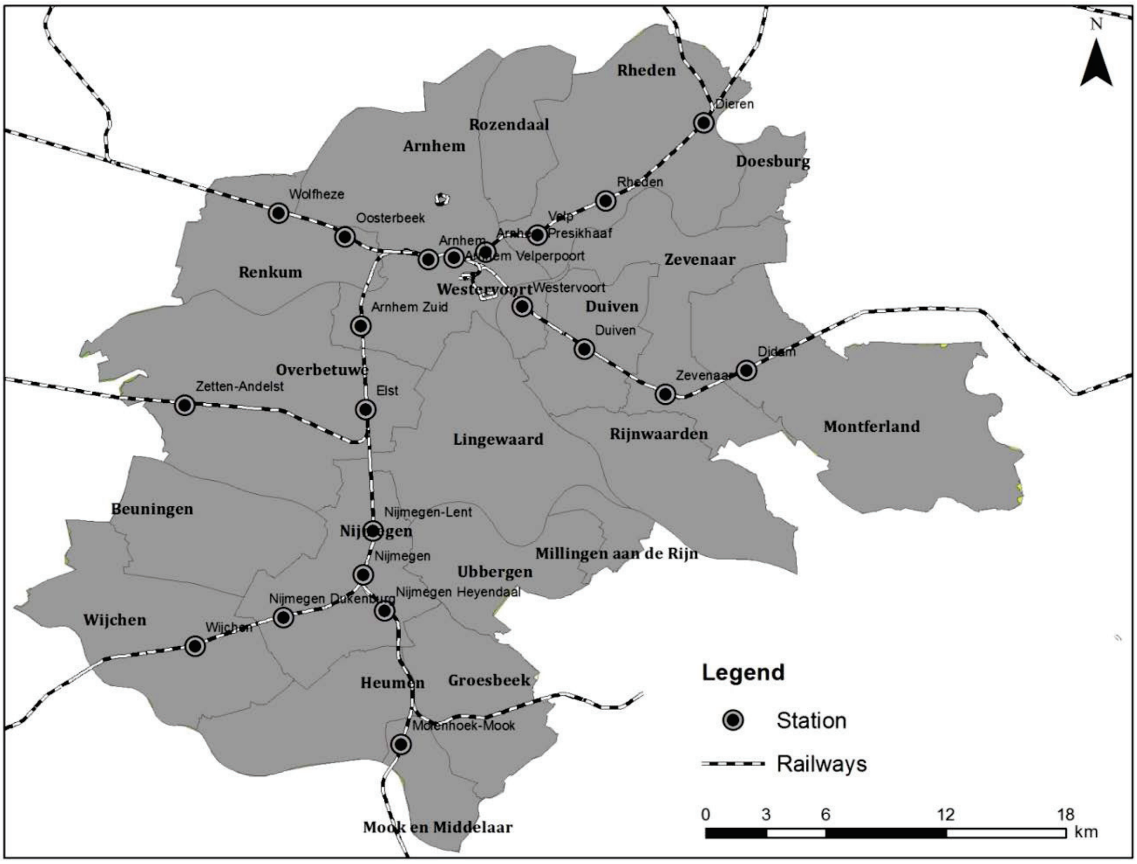


Figure 1-3 The Study Area: Stadregio Arnhem-Nijmegen (SAN)

This region is situated near Ranstad, the fastest growing metropolitan area in the Netherlands. The region has ambition to become the second biggest economic area in The Netherlands after Ranstad by 2020. The region has presented itself as an attractive and easily accessible region with a strong competitive position worldwide. Therefore, it is important to encourage business activity in the area

There are 21 train stations operating in the region. Two largest stations are Station Arnhem and Station Nijmegen (Figure 1-4). The largest station, Station Arnhem while operating is also in renovation at the moment. There are 12 route connections of train from this station. One of these is international train which serves journey from Amsterdam Centraal to Frankfurt. The second largest station, Station Nijmegen, serve an important route that connects several important nodes: Nijmegen-Arnhem-Wageningen-Utrecht-Amsterdam. There are 7 route connections in this station.


Figure 1-4 Renovation plan of Station Arnhem (Left) and Station Nijmegen (Right)

TOD plans have been showing promising outcome of increasing regional economic and international competitiveness (Knowles, 2012). The stakeholders in the Arnhem Nijmegen Region also realize the benefit of TOD plans to the economic development in the area. Therefore, it is feasible to construct TOD index and implement it to the region. Cooperative attitude from stakeholders in the area should ease the process of data collection and stakeholder involvement (workshop).

One of the benefits of TOD planning is to increase location efficiency, which later in the next stage will improve the financial and economic condition. The TOD index will help the decision maker to determine which areas that has more potential to be developed mainly on business activities.

#### 1.5.3. Data Requirement and Collection

Most of data used in the research were derived from secondary sources. Some data were provided by SAN authority. The data from *Centraal Bureau voor de Statistiek* (CBS) were also used. As this research is part of bigger projects, the data were also derived from previously related project, and from currently parallel researches.

Data of building footprints was provided by SAN authority. Demographics data and administrative boundaries were derived from CBS, road network was collected from ESRI Nederland – TOP10NL. In addition to these, the station data were derived from Open Street Map (OSM). The information from google earth and google maps was occasionally used to verify some of the data. All of the spatial information is in vector representation in GIS. The data derived from secondary sources in this study is presented in Table 1-2.

Table 1-2 List of data used in this study

| Data Source | Features |
|---|---|
| SAN Authority | Building Footprints |
| | Number of Passenger in Daily Average |
| | Service Frequency |
| | Route Connections |
| | Parking Utilization (Car and Bicycles) |
| | Digital Display System |
| | Mode Interchange (Bus) |
| ITC former projects archive | SAN Topography (land use) |
| CBS | Administrative Boundaries |
| | Demographics Data |
| | Business and Commercial Activities |
| | Jobs |
| Esri Nederland - TOP10NL | Road Network |
| OSM | Train Stations Map |
| NS Website | Train Station Facilities |

Information about station services and facilities was derived from SAN authority and Nederlanse Spoorwegen (NS) website. NS is the largest train services in The Netherlands. Most of the trains in The Netherlands are operated by NS.

Primary data collection was conducted briefly to collect some information about the station and to observe surrounding environments around the station. Field visit was also useful to verify some information derived from NS Website. Field visit was conducted for three days to visit 21 stations in the SAN.

## 1.6. Structure of Thesis

**Chapter One: Introduction**

Chapter one describes the background and justification of conducting the research about TOD measurement. Then, the research problem is discussed, followed by defining the objectives and research questions. Conceptual framework is also presented followed by general design of the research (methods, operational plan, study area, and data).

**Chapter Two: Literature Review**

This chapter consists of literature review related to the TOD concept and measurement. The advantages offered by GIS platform and MCE are also presented in this part.

**Chapter Three: Identification of Criteria and Indicators**

Chapter three describes methodologies that have been used to produce the criteria and indicators in this research. The ideal indicators for calculating TOD index are presented in this part. Then, the selected indicator to be calculated as TOD index in this research, are presented in this chapter as well.

**Chapter Four: Calculation of TOD Index**

Chapter four presents the methodologies used to quantify selected indicators based on the data available. This chapter also describes the methodologies used to construct the composite index based on Multi Criteria Evaluation (MCE).

**Chapter Five: Result and Discussion**

The result of indicator quantification is presented at the initial part of this chapter. Then, the results of TOD index and values is presented, analysed, and compared. It is interesting to investigate the anticipated results such as the variation of TOD index in each transit node, the different influence of each aspect to the TOD values, and the effects of slight change in the weights towards TOD value (sensitivity analysis).

**Chapter Six: Conclusion and Recommendation**

This final chapter provides summary for the whole study, including important conclusions from the research, the remarks about methodology used, and the accomplishment of the objectives. Furthermore, the suggestions for improving TOD level of the stations in City Region Arnhem and Nijmegen is presented as well on this chapter.

# 2. LITERATURE REVIEW

"People are not simple and we should not attempt to make them so with cities and suburbs that limit their choices. I believe a diverse and inclusionary environment filled with alternative ways of getting around is inherently better than a world of private enclaves dominated by the car" (Calthorpe, 1993).

The phrases above represent the main goal of Transit Oriented Development (TOD) adopted in this study which is not to force people towards certain rigid way of living, but it intends to give people alternatives in conducting their daily activities. Therefore, TOD is not about forcing people out of their car to use public transport and other non-motorized alternatives of getting around, instead it is about creating 'environment' that encourages people to act and behave towards the sustainability of the city.

This chapter starts with how various literatures define TOD and how TOD is planned. The ways of TOD measured and evaluated are also presented on the basis of previous research about TOD measurement. This chapter also discussed the tools used in TOD measurement including Geographic Information System (GIS) platform and Multi Criteria Evaluation (MCE). Thorough examination of TOD concept in this chapter poses as valuable input for identification of criteria and indicators in next chapter.

## 2.1. Transit Oriented Development (TOD)

It was found that there is no universal definition of TOD. TOD is described uniquely by different stakeholders as they have different perspectives on the concept. To put it simple, this study started with the basic principal components of TOD defined by Calthorpe (1993) such as *mixed use*, *transit oriented*, *walkable* and *diverse*. *Mixed use* refers to the concentrated mixed development of various urban activities. Intensive mixed use development can lower the rates of vehicular travel (Cervero et al., 1997) and can encourage walking and bicycling in the neighbourhood (Belzer et al., 2002). *Transit oriented* explicitly stated that TOD is about the development around the transit nodes. *Walkable* means that the area should provide friendly environment for pedestrian. *Diverse* refers to diversity in activities (land uses) and diversity in people (communities). Both kinds of diversity are related to each other. TOD area should be composed by different type of activities and development that can provide choice for all people without limiting it into particular segment of communities (income, ages, or jobs). These four aspects are also repeatedly noted as important components of TOD in many other studies (Belzer et al., 2002; Cervero et al., 2008; Curtis et al., 2009; Renne, 2007; Schlossberg et al., 2003).

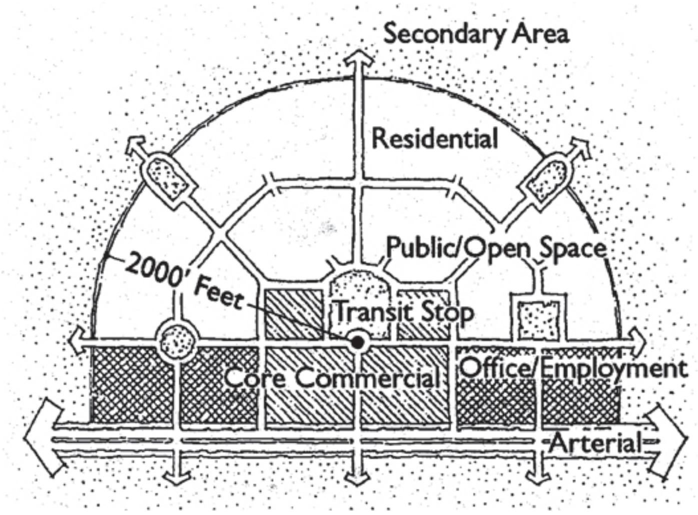


Figure 2-1 Illustration of TOD based on Calthorpe (1993)

Figure 2-1 depicts one illustration of TOD area based on Calthorpe (1993), which focused on the *physical characteristics* of TOD area such as mixed residential, retail, office, open space, resident's convenience while traveling using transit, foot, bicycle, and especially around the walkable environment.

## 2.2. TOD Planning

The basic principles of TOD planning according to Calthorpe (1993) are to encourage the following components.

- Compact growth and transit supportive at regional level.
- Mixed uses (commercial, residential, jobs, parks, and public space) within walking distance of transit nodes.
- Street network with pedestrian friendly environment.
- Diverse type of housing, densities, and costs.
- Maintaining open spaces and sensitive habitat.
- Neighbourhood activities and building orientation were concentrated toward public spaces.
- Infill and redevelopment of existing neighbourhood around the transit corridors.

In line with that, Boarnet et al. (1997) and Parker et al. (2002) also emphasized more on the physical aspects such as intensifying *residential land use* and encourage *moderate to higher density* development. On the other hand, Dittmar et al. (2004) defined TOD from the perspective of performance based view. They argued that the main goal of TOD is not to create physical form but rather to create places that *function* differently than conventional development.

Performance based view was also adopted by Belzer et al. (2002) and Dorsey et al. (2013) to define TOD. Belzer et al. (2002) argued many projects claimed as successful TOD do not function well, because they focused more on physical characteristics rather than performance. Performance criteria are represented by the following components (Belzer et al., 2002).

- *Location efficiency* - It requires neighbourhood with good quality of transit, mixed use development, and pedestrian friendly environment. The aim is simply to change *driving* from a need into an option.
- *Value recapture* - Better transit quality lead to reduced spending on transportation by households, developers, and local governments.
- *Liveability* – TOD improved the quality of life through improved air quality, less gasoline consumption, decreased congestion, greater mobility, etc.
- *Financial Return* – Mixed use strategy can be advantageous return of investment for both public and private.
- *Choice* – Diverse activities and development provide diverse flexibility and opportunity for various segments of individual and community.
- *Efficient* regional land use patterns – Concentrated development around station means less land consumed, less traffic generated, less congestion, and less pollution, compared to typical suburban development.

Calthorpe (1993) divided TOD into two types with different characteristics, which are urban TOD and neighbourhood TOD. Urban TOD is located along trunk line of transit network, characterized by high commercial intensities, diverse jobs locations, and moderate to high residential densities, while the neighbourhood TOD is located on local of feeder bus line within 10 minutes transit travel time, characterized by moderate density residential, retail, service, recreational uses, entertainment civic and recreational uses (Calthorpe, 1993). Kamruzzaman et al. (2014) also noted the importance of TOD typology in TOD planning, and they introduced six types of TODs e.g. city centre, activity centre, specialist activity centre, urban, suburban and neighbourhood.

As the city is a part of the bigger system, CTOD (2011) emphasized that TOD planning needs to be conducted at regional level, urban level and local level. However, the scale of TOD planning at nodes level plays significant role since the activities are oriented towards the transit nodes. Singh et al. (2012) found that TOD should be planned on various scales such as station area level, transit corridor level and urban regional level.

## 2.3. TOD Measurement

As the concept is perceived differently, the measurement of TOD is also conducted variously by different scholar. TRB (2007) stated the needs to measure the existing TOD in form of 'index' and mentioned the *most 'quantifiable' aspects* of TOD. The research by TRB (2007) selected ten most useful indicators to measure the success of TOD, which are transit ridership, density, quality of streetscape design, quantity of mixed-use structures, pedestrian activity, increase in property value, public perception, mode connections at the transit station, and parking configuration. However, this research did not conduct the measurement of these indicators.

Loo et al. (2010) examined the relationship between some variables about transportation, built environment, and planning towards transit ridership for TOD area in Hongkong and New York Cities. The study aims to examine the factors that influence transit ridership and to quantify their relationship. The aim of using the two cities as case studies is to examine the common factors influencing transit ridership in the hope of developing useful policy implication to promote TOD. The variables are grouped under four dimensions which are land use, station characteristics, socio-economic and demographic characteristics, and intermodal competition. The variables used by Loo et al. (2010) are similar with the indicators found before e.g. total commercial/residential floor area, total commercial floor area, mixed land use, population size and employment, and number of bus stops within the station buffer (walkability limit).

Schlossberg et al. (2003) compared the TOD level of transit station in Portland based on the walkability indicators using GIS based walkability measures. The result is the rank of eleven TOD areas around transit nodes in Portland. Schlossberg et al. (2003) argued that a combination of a visual spatially-based analysis with the quantification of walkable urban form can provide planners and policy makers useful information about the performance of existing or potential TOD areas.

After conducting the careful examination of literatures regarding TOD measurement, Singh et al. (2012) suggested to use a set of six performance criteria proposed by Belzer et al. (2002), which are *location efficiency, value recapture, liveability, financial return, choice of lifestyle* and efficient *land use pattern* at regional level. Belzer et al. (2002) admitted that various definitions of TOD in different literatures, emphasize more towards physical form or design rather than functional outcomes it should achieve. However, the data required for these criteria are incredibly intensive. The collection of these data can be an exhausting procedure and sometimes is not even possible (Singh et al., 2012). Therefore, it is quite a challenging task to translate these criteria into meaningful indicators that can be quantified efficiently.

Singh et al. (2012) proposed a design framework to measure the TOD level as depicted in Figure 2-2. This framework has been operationalized by Fard (2013) to measure the potential TOD index for the entire area of city region Arnhem Nijmegen (SAN). Using the same framework, this study attempts to construct TOD index for each station based on the existing condition.

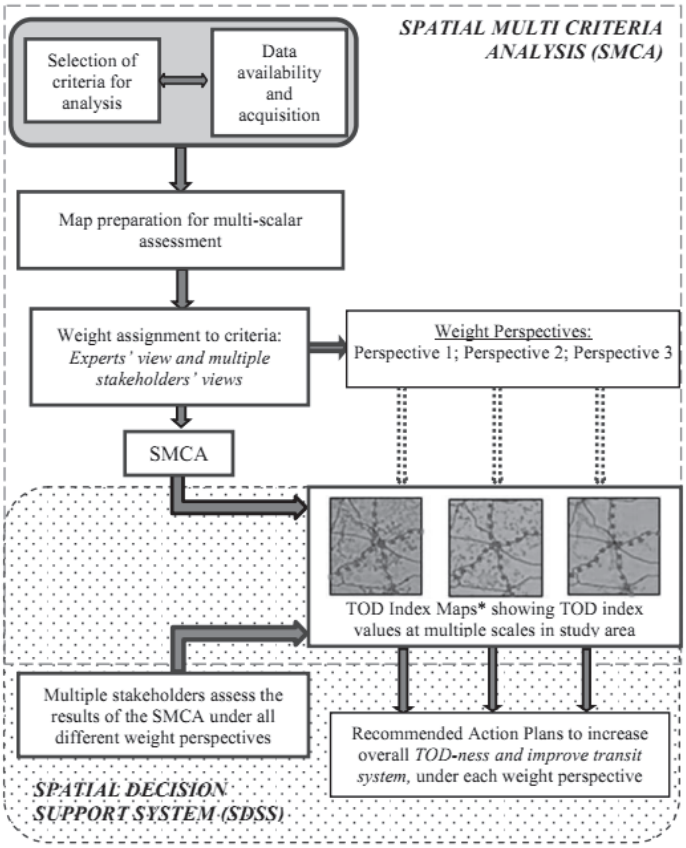


Figure 2-2 Design framework for measuring TOD index (Singh et al., 2012)

GIS has been proven useful to provide good platform of spatial analysis for the research about TOD measurement. Most the TOD studies employ the spatial analysis using GIS platform (Cervero et al., 1997; Schlossberg et al., 2003; Sung et al., 2011). Schlossberg et al. (2003) conducted spatial analysis and network analysis within GIS platform in order to produce 11 walkability indicators based on three primary techniques such as network classification, Pedestrian Catchment Areas (PCA), and intersection densities. The framework presented in Figure 2-2 implied the need of using GIS platforms since it deals with maps.

Singh et al. (2012) also emphasized the importance of multi criteria assessment or Multi Criteria Evaluation (MCE) tool to aid the process of construction the TOD index. It was believed as a method in spatial planning to explore and solve complex problems to aid the decision making processes (Iojă et al., 2013; Jeong et al., 2013). The decision making using MCE can quantitatively evaluate the alternatives, and it can incorporate different perspectives and priorities to produce common output (Convertino et al., 2013; Iojă et al., 2013).

# 3. IDENTIFICATION OF CRITERIA AND INDICATORS

## 3.1. The Methods of Defining Criteria and Indicators

Dopheide et al. (2007) defined *indicator* as "qualitative or quantitative data that describe features of a certain phenomenon and communicate an assessment of the phenomenon involved", and it serves as variable to measure aspects of development according to common goals that can be expressed in numerical terms. Likewise, Litman (2008) defined "indicator as variable selected and defined to measure progress toward an objective". In this research, the objectives or common goals of TOD are called as *criteria*. The criteria represent the ideal condition that should be met for each important *aspect* of TOD. Along with the criteria, the *hypotheses* were defined as how the contribution of each criterion toward TOD level is.

In this research, the selection of indicators employs top down approach. This approach, based on Weiland et al. (2011), is known as 'deductive approach', which derived by researchers on the base of a scientific concept. Firstly, various view on the TOD concept are presented in order to gain understanding about Transit Oriented Development around transit nodes and to identify the main aspects of the TOD. Secondly, the aspects are translated into criteria and hypothesis. Then, the indicators are selected on the basis of these criteria. Basically, the criteria and indicators were constructed based on the framework suggested by Singh et al. (2012), and the work of Singh (2013), enriched by various literatures either to support to criticize them. Figure 3-1 depicts the process.

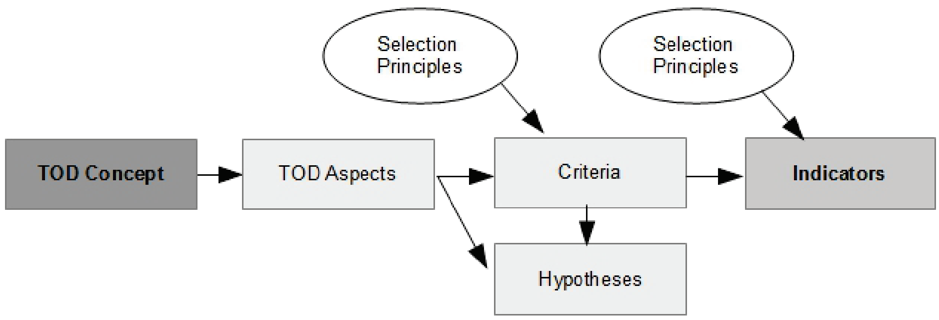


Figure 3-1 Top-down approach of indicators selection for TOD Index

There are many principles of conducting indicator selection based on various literatures. Several authors noted that the indicators should be comprehensive, measurable, possible to quantify, understandable, reasonable, clearly defined, accessible, reflect various aspect of study, sensitive to changes overtime, independent, and capture long-term processes (Haghshenas et al., 2012; Litman, 2008; Zhang et al., 2006). Haghshenas et al. (2012) summarized the *selection principles* into three categories: representation (validity, reliability, sensitivity), operation (measurability, data availability, ethical concerns), and policy application (transparency, interpretability, target relevance, action ability). Meanwhile, Kurka et al. (2013) mentioned that criteria and indicators should be operational and meaningful, complete in regard to all goals, non-redundant, few and manageable in number, applicable, transparent, reliable, and appropriate.

After careful examination of the literatures, it was decided that this research will use *two* selection principles for defining the criteria and use *seven* selection principles for selecting indicators. The selection principles for defining *criteria* are presented as follow.

1. *Relevance*. The criteria should represent the important aspects of TOD as indicated in many literatures.
2. *Comprehensive*. The criteria should cover all the important aspects of TOD.

Then, the selection principles for *indicator* selection are presented below.

1. *Relevance* towards current level of TOD (represent the criteria/hypotheses)
2. *Practical* to be measured.
3. Indicators should be *clear*.
4. *Efficient* in terms of resources required (less data demanding).
5. It should be *applicable* and *replicable* for other contexts beyond the study area.

The indicators produced up until this stage, are considered as *ideal indicators* for the TOD index. However in this research, the calculation and the implementation of TOD index will take a case study in city region Arnhem and Nijmegen. Therefore, not all of the ideal indicators can be included in the TOD index calculation. Some will be dropped or modified based on the next two selection criteria as follow.

6. *Data Availability*. The indicators will be dropped or modified to adapt with data availability in the study area.
7. *Significance*. The indicators will be dropped in case it has no variation between the stations in the region.

## 3.2. Defining Aspects, Criteria, Hypotheses, and Indicators

On the basis of the literature review in previous chapter, there are *eight aspects* of TOD identified in this studies. The following part will describe in detail about the aspects along with the *criteria*, *hypothesis*, and *the indicators*.

### 3.2.1. Utilization of Transit Nodes

It was found that many literatures indicate the transit ridership as one main aspect of TOD. Several studies argue that there is a relationship between transit ridership and TOD planning factors such as land use characteristics, built environment, and design characteristics (Loo et al., 2010; Sung et al., 2011). Sung et al. (2011) emphasized the importance of transit ridership toward TOD planning factors because it reflects the transit system service level. Moreover, Loo et al. (2010) examined the common factors influencing transit ridership in order to develop useful policy implication to promote TOD in two cities (New York and Shanghai). Likewise, Renne (2007) reveals nine indicators of performance as the most important for TOD evaluation framework, and transit ridership is one of these.

The research by TRB (2005) reveals that transit ridership is one of most useful indicators for evaluating TOD in United states, along with other indicators e.g. density, quality of streetscape, quantity of streetscape, quantity of mixed-use structures, pedestrian activity and safety, increase in property value and tax revenue, public perception, number of mode connections at the train station, and parking.

The utilization of transit nodes, however, despite it has relation with transit ridership, served different purpose. While transit ridership is looking at the increase in the number of transit user, utilization also looks at the capacity in determining optimum level of service.

**Criteria:** Transit system should have optimum capacity utilization. TOD cannot be planned for those stations where capacity utilization is saturated.
**Hypothesis:** Transit system with optimum capacity utilization has higher TOD level.

The indicators used to represent the utilization of transit nodes are *passenger load* during *peak hour* and passenger load during *off-peak* hour. Both are a good proxy for transit ridership. These were indicated in some research about TOD (Loo et al., 2010; Renne, 2007; Singh et al., 2012). While Renne (2007) and Loo et al. (2010) look at the average boarding during weekdays, Sung et al. (2011) goes more detail by breaking down average daily user based on day of the week (weekday or weekend), mode used (bus, subway, or transfer), time of the day (morning peak or morning non-peak).

"Transit is less attractive when passengers must stand for long periods of time, especially when transit vehicles are highly crowded. When passengers must stand, it becomes difficult for them to use their travel time productively, which eliminates a potential advantage of transit over the private automobile. " (TCRP, 2003). Therefore, it is important to ensure that the passenger load is at optimum level in order to encourage the use of public transit. Lower passenger load indicates the less people using public transit and the waste of resources (train capacity), while high passenger load indicates overcrowding which can discourage people using public transit.

The term p*assenger load* reflects how loaded a system is. It measures the total number of passenger/capacity. "*Loading levels* for commuter rail are unique and uniform. Although standing passengers may be accepted for short inner-city stretches or during times of service irregularities, the policy is to provide a seat for all passengers. *Capacity* is usually cited at **90 to 95%** of the number of seats on the train" (TCRP, 2003).

### 3.2.2. User friendliness and attractiveness of the transit system

The importance of the quality of transit system plays important role to encourage people using less of the private transport (Newman, 2009). Similarly, Renne (2007) put the quality of transit system as one of most important aspect in TOD evaluation. As TOD planning aims to encourage the use of public transport, the quality of transit system contributes significantly in this matter.

TCRP (2003) emphasized *two* important factor influencing the transit decision-making process, which are the *availability* of transit system and the *comfort and convenience* of transit system. The availability can be divided into the following components.

1. Spatial availability. Where is service provided, and can one get it?
2. Temporal availability. When is service provided?
3. Information availability. How does one use the service?
4. Capacity availability. Is passenger space available for the desired trip?

The second factor, comfort and convenience, consists of service delivery, travel time, safety and security, and maintenance(TCRP, 2003).

**Criteria:** Transit nodes should be user friendly and attractive.
**Hypothesis:** The more user-friendly is transit system, easier it is to plan for TOD.

The indicators used to represent this criterion are *safety, amenities*, and *passenger circulation*. Safety is related to risk of transit user to be involved in an accident or the risk of becoming the victim of crime while using transit. Safety includes the *safety of passenger while waiting in the station* and *the safety of passenger while being inside the train*. The amenities consist of the presence of shelters, waiting room, benches, vending machines, shop and restaurants, and lighting. Passenger circulation is generally indicated by the layout and design of train station such as condition of stairway, access for disabled, the presence of signage, and the presence of information display.

### 3.2.3. Accessibility

Accessibility is ubiquitous in transport and land use planning these days. Most of the studies realize the importance of accessibility rather than merely focusing on mobility. Undoubtedly, access is one of the key aspects in accomplishing TOD (Belzer et al., 2002; Cervero et al., 2008; Curtis et al., 2009; Schlossberg et al., 2003; TRB, 2005). Belzer et al. (2002) noted that the transit agencies plays important role to create great accessibility and interconnection of the transit nodes.

Schlossberg et al. (2003) argue that the successful TOD is largely dependent on the capacity of transit users to access the transit stop to begin with or to access the key destinations once the transit user reaches his/her destination. Similarly, Belzer et al. (2002) noted that "station areas must prove access to transportation services in many cases function as regional trip destinations, but the same areas must also serve as trip origins and, ideally, as coherent neighbourhoods that do more than simply serve the station".

**Criteria:** Transit nodes should be accessible and provide good accessibility for surrounding area.
**Hypothesis:** A node with better access and that provides high accessibility, has increased chances of successful TOD.

There are five indicators used to represent this criterion. The first one is *service frequency of transit system*. This indicator is related to the temporal availability of transit system as mentioned in the previous part. The more frequent transit operates, the more accessible the transit is for the passenger because the passenger does not have to wait for a long time to use the transit. Moreover, high service frequency also increases the capacity of transit services which can reduce the crowdedness in the transit. The second one is *number of route connections*. If the station has more connection to the different routes, then the passengers have better access to different part of city/region.

The third indicator is *number of interchange to other mode*. The other modes of transit can be bus, tram, subway, water transportation, or plane. The passengers have better access to the various destinations if more of these modes are available. The fourth indicator is *access to the station*. It is the level of access to the station by all modes. It can be measured by using local spatial and temporal availability that looking at the total population served by transit node, and measuring the service availability during a defined service period. This calculation is very data demanding.

The fifth indicator is *location-accessibility provided by the station*. This indicator is the measure of total number of opportunities that can be accessed within the TOD area. This measure is also known as cumulative opportunity measure.

### 3.2.4. Parking

The research by TRB (2005) put parking configuration as one of most useful indicators to evaluate TOD. Renne (2007) also considers parking configuration as important indicators for evaluating TOD, but the focus should be on the availability of parking for non-motorized transport (bicycles) and the availability of parking for commuter groups. Moreover, since the study area is in the Netherlands where the bicycles are used by most of the population, the availability of bicycle parking is essential.

However, walking and biking are not always the primary access mode to the transit. Park and ride facilities for automobile are also required in many stations, especially in the lower-density areas where fixed-route services is not economical, as it focuses transit boarding demand to a small number of points (TCRP, 2003).

**Criteria:** Transit station should provide optimum parking supply for different modes.
**Hypothesis:** The availability of parking space for different modes will encourage the use of transit system. Hence, it produces higher level of TOD.

There are three indicators used to represent the criteria of optimum parking supply, which are *parking supply-demand for cars, parking supply-demand for cycles* and *reserve car parking for special commuter* groups. Parking supply-demand looks into the utilization of parking spaces, which is the ratio between the parking user and the capacity of parking available. Lower parking utilization indicates the parking service is not optimum. On the other hand, high parking utilization indicates the capacity is saturated. In case of parking for motorized vehicle, occupancy rates close to 100% should be avoided because it encourages illegal parking (City of Mill Valley Authority, 2008). Since the TOD planning encourages the use of public transit, more demand for parking will arise. Therefore, there should be some 'reserved' space for this expected growth.

Based on the research by City of Mill Valley Authority (2008), optimum parking is achieved when it is 85% occupied for on-street parking, and it is 90% for off-street parking. These standards are applied for parking for motorized vehicle. Because the standard for bicycle parking cannot be found, this study considers the standard of parking between motorized vehicle and bicycle as the same. In this research, the optimum utilization of parking space is decided at 90%.

The research also incorporates the presence of car parking space for special commuter groups. The space is provided for the residents or frequent commuters which work further away and live a little bit far from the station (outside of walking distance). It intends to encourage residents to take a small ride to the station and use the transit to work, instead of using the cars for the whole journey.

#### 3.2.5. Density

The densities of built environment around the walkable limit is indicated important by most of the research about TOD (Belzer et al., 2002; Boarnet et al., 1997; Calthorpe, 1993; Cervero et al., 1997; Curtis et al., 2009; Dittmar et al., 2004; Loo et al., 2010; Parker et al., 2002; Sung et al., 2011). Parker et al. (2002) mentioned moderate to higher density development as part of TOD. Boarnet et al. (1997) argued about the importance of intensifying residential land use around the station.

"*Compact neighbourhoods* can degenerate vehicle trips and encourage non-motorized travel in several ways. One, by bringing origins and destinations closer together, there become many more opportunities for leaving one's car at home and walking or cycling to a destination. Moreover, compact neighbourhoods tend to have less parking, better quality transit services, wider mixes of land uses, and larger shares of low income households, all factors that reduce car usage"(Cervero et al., 1997).

**Criteria:** TOD area must have a minimum transit supportive density. If densities are less, then efforts are required to bring them up to a certain level.
**Hypothesis:** An area with density from moderate to high densities has higher TOD level.

The indicators used to represent this criterion are *population density* and *commercial density*[3]. Population density is the measure of people who live in the residential area within the walking distance from the station while the commercial density is looking at the number of commercial activities within the walking

[3] There is one more density indicator used in this study, which is *business density*. This indicator is used in different criteria. It is part of economic development criteria which will be discussed in the next part.

distance from the station. Both land use, residential and commercial, are indicated by many research as important part of TOD planning (Calthorpe, 1993; Cervero et al., 1997; Zhang et al., 2006) . However it should be noted that density factor should be balanced with other built environment factors, because focusing only on density factor can cause many inner city problems such as overcrowding, traffic congestion, and reduced quality of life.

### 3.2.6. Land Use Diversity

Similarly with the previous one, the land use diversity is also addressed as one of most important aspect of TOD by numerous experts (Belzer et al., 2002; Boarnet et al., 1997; Calthorpe, 1993; Cervero et al., 2008; Cervero et al., 1997; Curtis et al., 2009; Dittmar et al., 2004; Loo et al., 2010; Parker et al., 2002; Renne, 2007; Sung et al., 2011; TRB, 2007; VTPI, 2012). Cervero et al. (1997) explicitly expressed the diversity as main components of TOD through his 3Ds (Density, Diversity, and Design) concept. Diverse type of housing and diverse activities within the walking distance around the transit nodes, would provide more *choices* for the residents (Belzer et al., 2002).

**Criteria:** TOD area should have diverse land use so it can create vibrant and liveable environment within the walking distance.
**Hypothesis:** TOD area with more diverse land use has better TOD level.

*Land use diversity level* is the one and only indicator used to represent this criterion. This indicator examines the multiple destinations within the walking distance from the station. It measures how diverse the functional land use is. Cervero et al. (1997) introduced several methods to calculate diversity such as dissimilarity index, entropy, vertical mixture, activity centre mixture, and commercial intensities.

### 3.2.7. Walkable Environment

Calthorpe (1993) defined TOD as "a mixed use community within an average 2000 foot walking distance of a transit stop and core commercial area. TOD". He emphasized on walkable environment as key aspect of TOD. Similarly, Cervero et al. (1997) also mentioned pedestrian friendly environment as the key factor to complement his 3Ds (Density, Diversity, and Design) concept.

Schlossberg et al. (2003) summarized that an effective TOD relies on several factors such as higher than average density, land use mix, roadway connectivity and design and building design. Moreover, the study argued that the core component of TOD success lies in the capacity of users to access the transit stop and the immediately surrounding area which is often accomplished by foot or local transit connection (Schlossberg et al., 2003). While acknowledging the importance of density and land use mix for TOD, the research by Schlossberg et al. (2003) focused on the walkability factors as one of key component for TOD.

**Criteria:** TOD area should have pedestrian friendly environment.
**Hypothesis:** Pedestrian friendly environment will provide better access to various attractions within the TOD area and will encourage the people to move around TOD area by foot.

There are *five* indicators used to represent this criterion. The first one is *level of land use mix*. This indicator looks into the mix between residential land uses and other functional land uses within the TOD area. The higher mix level indicates the likelihood of residents to do walking to reach various destinations within the TOD area. This indicator is different with the land use diversity level discussed earlier. While the land use diversity examines the multiple destinations (activities) from the station, the mixed use level looks into the residents' preference of walking from their home toward the surrounding environments.

All of the remaining indicators within this criterion were derived based on the work of Schlossberg et al. (2003). The second indicator is *quantity of accessible path,* which looks into the availability of paths that can be accessed for walking within the TOD area. Higher quantity of accessible path indicates that the area is more walkable. The third indicator is *intersection density*. It measures the number of intersections/junctions within the TOD area. Higher number of intersections implied that the network has higher level of connectivity (Aurbach, 2010; Kamruzzaman et al., 2014). Hence it gives better access to pedestrian[4].

The fourth indicator is the *density of dead ends*. Dead ends limit the movement of pedestrian. Therefore, higher density of dead ends indicates that the area is less walkable. The fifth indicator is *Impedance Pedestrian Catchment Areas (IPCA)*. This is the measure of walkable area of pedestrian in the TOD area within ten minutes based on the movement along the accessible path (Schlossberg et al., 2003).

### 3.2.8. Economic Development

Dittmar et al. (2004) give performance based definition of TOD. The main goal of TOD is not to create physical form but rather to create places that function differently than conventional development. Belzer et al. (2002) claimed that most of TOD definitions emphasize more on the physical and design aspects and They proposed a set of six performance criteria which are quite similar with the criteria introduced by Dittmar et al. (2004) e.g. location efficiency, value recapture, liveability, financial returns, choice of lifestyle, and efficient land use pattern.

Both studies above noted the importance of financial returns as of the important aspect of TOD. This aspect is part of the economic development in the area. Moreover, Renne (2007) and TRB (2005) used another aspect related to the economic development for evaluating TOD, which is increased in property value/tax revenue. Cervero et al. (2008) revealed that the residential area located around the rail station has an advantage of having higher job accessibility, compared to the residential area located far away from the rail station. TOD area offers high job opportunities which are related to the employment level.

**Criteria:** TOD area should have better economic development so it can engage people in the surrounding area into various activities.
**Hypothesis:** Areas with higher economic development should have higher TOD levels.

There are four indicators used to represent this criterion. These are business density, private investments of municipalities, tax earning of municipalities, and employment levels.

[4] Research by Schlossberg et al. (2003) considers higher intersection density as negatively associated with the walkability. However, other studies suggested otherwise. Hence this study put intersection density as positively associated with the walkability.

### 3.3. The Criteria and Indicators

On the basis of indicators identification in the previous part, the list of indicators had been produced and this is presented in the Table 3-1. This list is considered as ideal indicators. There are *8 criteria* and *25 indicators*.

Table 3-1 List of Ideal Indicators

| Criteria | Indicators |
|---|---|
| a) Transit nodes should have optimum capacity utilization | 1. Passenger load in peak hours |
| | 2. Passenger load in offf-peak hours |
| b) Transit nodes should be user friendly and attractive | 3. Safety |
| | 4. Amenities |
| | 5. The presence of information display system |
| c) Transit nodes should be accessible and provide good accessibility | 6. Service frequency of transit system |
| | 7. Number of connections to different routes |
| | 8. Number of interchange to other mode |
| | 9. Access to the station/stop |
| | 10. Location-accessibility provided by the station/stop |
| d) Transit nodes should provide optimum parking supply for different modes | 11. Parking supply-demand for cars/four wheelers |
| | 12. Parking supply-demand for cycles |
| | 13. Reserved car parking for special commuter groups |
| e) TOD area should have a minimum transit supportive density. | 14. Population (residential) density in TOD area |
| | 15. Commercial intensity/density in TOD area |
| f) TOD area should have mixed use so it can create vibrant & liveable environment | 16. Diversity of land uses |
| g) TOD area should have pedestrian friendly environment | 17. Level of mixed-ness of land uses |
| | 18. Quantity of accessible path |
| | 19. Impedance Pedestrian Catchment Areas (IPCA) |
| | 20. Intersection density |
| | 21. Dead ends density |
| h) TOD area should have better economic development | 22. Private investment in municipalities |
| | 23. Number of business establishments |
| | 24. Tax earnings of municipalities |
| | 25. Employment levels |

However, not all of the indicators could be incorporated further into the research. Some indicators cannot be calculated due to *data availability* issues. Some were dropped because they have the same value for all the stations, hence these indicators do *not* contribute *significantly* to the TOD index. Some indicators also had to be modified for both reasons.

Out of *25 indicators* identified, *seven* of these were not included for further analysis. These are *amenities*, *access to the station, reserved parking for commuter, dead ends density, private investment, tax earning,* and *employment levels*. Some indicators also had to be *modified* in accordance to data available. Therefore, there are *18 indicators* to be used further in this research, as presented in the Table 3-2.

Table 3-2 List of Selected Indicators

| Criteria | Indicators |
|---|---|
| a) Transit nodes should have optimum capacity utilization | 1. Passenger load in peak hours<br>2. Passenger load in off-peak hours |
| b) Transit nodes should be user friendly and attractive | 3. Safety of passenger in the transit stop<br>4. The presence of information display system |
| c) Transit nodes should be accessible and provide good accessibility | 5. Service frequency of transit system<br>6. Number of connections to different routes<br>7. Number of Interchange to other mode<br>8. Location-accessibility provided by the station/stop* |
| d) Transit nodes should provide optimum parking supply for different modes | 9. Parking supply-demand for cars/four wheelers<br>10. Parking supply-demand for cycles |
| e) TOD area should have a minimum transit supportive density. | 11. Population (Residential) density in TOD area*<br>12. Commercial intensity/density in TOD area* |
| f) TOD area should have mixed use so it can create vibrant & livable environment | 13. Diversity of land uses* |
| g) TOD area should have pedestrian friendly environment | 14. Level of mixed-ness of land uses*<br>15. Quantity of accessible path*<br>16. Impedance Pedestrian Catchment Areas (IPCA)*<br>17. Intersection densities* |
| h) TOD area should have better economic development | 18. Business density* |

*spatial indicators

The indicators above are divided into *spatial* and *non-spatial indicators*. Spatial indicators were indicated by asterisk (*) symbol. More detailed explanation about these two categories is presented in the next chapter.

# 4. CALCULATION OF INDICATORS AND TOD INDEX

## 4.1. Methods to Quantify The Indicators

The measurement of TOD index focuses on the area around the transit nodes (train stations). The TOD area is defined as the walking limit from the station. Various definitions of walking limit are given in literature. Schlossberg et al. (2003) defined the good walkable distance of urban form range somewhere within one quarter mile (400 m) and one half mile (800 m), while Calthorpe (1993) stated that the comfortable walking distance for a majority of people is within 2000-foot (610 m) radius. This research used the walking limit based on the suggestion from authority in city region Arnhem-Nijmegen (SAN). The study by SAN authority shows that *800 meters* is a comfortable *10 minutes* walking distance in The Netherlands.

Circular buffers were created within 800 meters of each station in SAN. There are two stations which its buffer overlaps each other. These stations are Arnhem and Arnhem Velpelpoort. In this case, the overlapping area is counted twice for every indicator calculation which incorporates the use of station buffer.

The processes of index quantifications vary depending on the nature of the indicators. Basically, the indicators can be divided into 2 general categories: *spatial* and *non-spatial* indicators. Non-spatial indicators are calculated using direct statistical or observational data without employing any spatial analysis. Some examples of non-spatial indicators are passenger load, safety in transit, frequency of service, number of route connections, parking utilization, etc. On the other hand, spatial indicators require certain spatial analysis in the process of calculation e.g. land use diversity, mixed use level, accessible path, intersection density, pedestrian catchment area, location accessibility, etc. While the calculation of non-spatial indicators is not directly affected by the buffer 800 meters around the station, the calculation of spatial indicators depends largely on this buffer size.

Except for the passenger load, non-spatial indicators are generally rather straightforward to be derived. It is available as direct value attributed to the station that may requires basic statistical analysis e.g. average, sum, ratio, maximum, or minimum. On the other hand, spatial indicators employed many more various methods in the process. Even, some of them posed challenges on how to find the appropriate method to calculate or aggregate.

To ease the explanation, this part is started with the methods of calculating spatial indicators, followed by methods of calculating non spatial indicators. The spatial indicators were indicated by asterisk (*) in Table 3-2. All the result of indicator calculation is presented at the next chapter in Table 5-1 and Table 5-2.

### 4.1.1. Calculation of Density Indicators

The main land use data source used to calculate this indicator is the *building footprint* data. This data contains the building footprints and the function of each building. However, out of 20 municipalities in the region, there is one municipality (Mook en Midelaar) has no building footprints data. So, for this municipality, the second source was used. This second source is *SAN topography* that contains land use data covering the whole area of SAN. Both data are presented in APPENDIX B.

The building footprints and land use data were *reclassified* to be used further in the analysis. The new classes as the result of reclassification are residential, commercial, industry, office, health, education, and sport. After reclassification, functional land use in SAN Topography (Residential and Commercial) which is belong to municipality Mook en Middelaar were combined with building footprints data. Figure 4-1 explains the process.

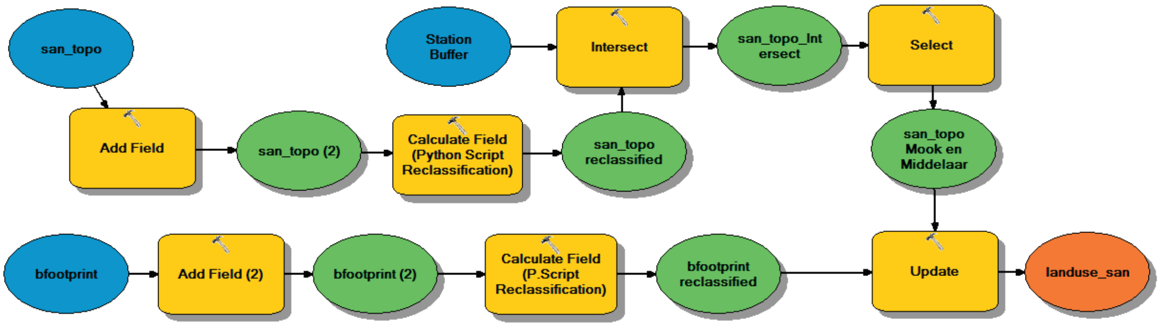


Figure 4-1 GIS Model used to prepare the land use data

In addition to the land use map, the data used for density indicators were derived from Centraal Bureau voor de Statistiek (CBS) 2007. This data contains information about *number of population* and *number of business*. Number of business is divided into industry, *commercial,* and business non-commercial

The data was available at *neighbourhood level*, while the unit of analysis in this research is area of 800 meters around station. Therefore, the neighbourhood data needs to be aggregated into buffer area of 800 meters around station. *Data apportion for non-coterminous polygons* were performed to produce aggregated data per station. The proportion of specific building footprints within each neighbourhood was used to approximate specific number of activities. The process of this method is presented based on the Figure 4-2.


Figure 4-2 Illustration of data apportion method for non-coterminous polygons

To calculate the *first density indicator* (population density), the proportion of *residential land use* was used to approximate *number of population.* Number of population per station area was approximated based on the proportion of residential land use of each neighbourhood that falls into station buffer. The entire process of producing number of population is presented by the Figure 4-3.

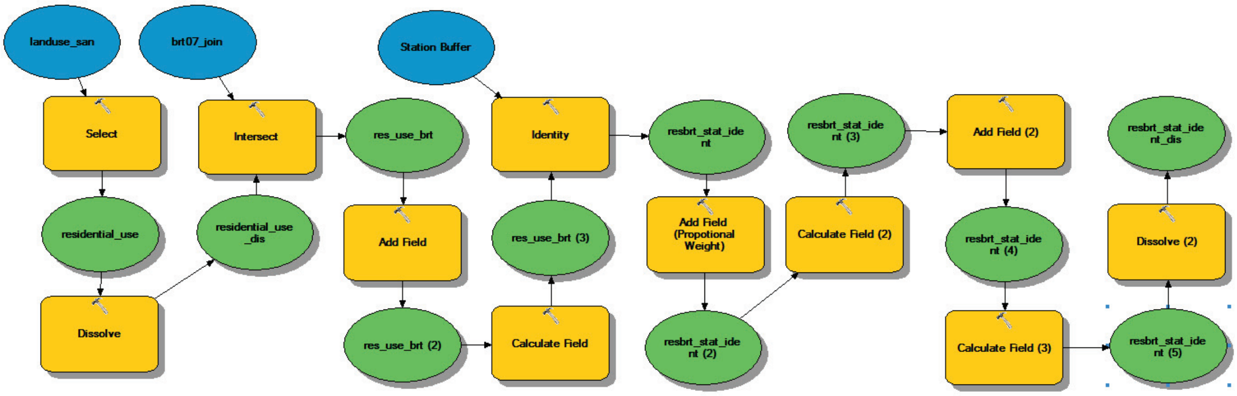


Figure 4-3 Process of calculation the number of population within TOD Area for each station

After the number of population was produced, the population density was calculated by dividing number of population with the size of TOD area (2.009492 $km^2$). Therefore, the unit of measurement for population density is number of population per square kilometre.

Similarly, *commercial density* and *business density* were calculated using the same method of calculating population density demonstrated earlier. The proportion of business land use and proportion of commercial land use were used to approximate number of both activities. Because the input data is number of activities, so the unit of measurement for both indicators is number of activities per square km.

It should be noted that the building footprint data used to approximate the proportion above, has no information about number of floor for each building. Therefore, it was assumed that all of the buildings only have one floor.

### 4.1.2. Calculation of Land Use Diversity Level and Mixed Use Level

The *land use diversity* level was measured using the notion of entropy which had been widely used to measure the level of diversity. Ritsema van Eck et al. (2008) put entropy formula as an alternative measure of simulating land use diversity in Dutch spatial planning. This study calculated the level of land use diversity based on the formula used by Fard (2013), as presented in Figure 4-4.

$$LU_d(i) = \frac{-\sum_i Q_{lui} \times \ln(Q_{lui})}{\ln(n)}$$

$$\sum_i Q_{lui} \times \ln(Q_{lui}) = Q_{ai} \times \ln(Q_{ai}) + Q_{bi} \times \ln(Q_{bi}) + \cdots + Q_{hi} \times \ln(Q_{hi})$$

$$Q_{lui} = \frac{S_{lui}}{S_i}$$

Figure 4-4 Entropy formula to calculate land use diversity level (Fard, 2013)

Si = Total area of the analysis window i
Slui = Total area of the specific land use within the analysis window i
n = Total number of land use classes within the analysis window i

Since the research by Fard (2013) is measuring the land use diversity for the whole region in SAN, it is important to create analysis window based on the grid cells. But, this study only focuses in the area 800 meters around station. Therefore, the formula was adapted in this research by replacing window of analysis into buffer area around the station. So, while the result of Fard (2013) produced index for each window of analysis in the whole region, the results of calculation in this study are land use diversity index for 21 stations. The value of diversity index ranges from 0 to 1. Value 1 represents highest diversity level.

The data used to calculate land use diversity is similar with the data used in calculating density. It employs the building footprints data. This data was also used to calculate the *mixed use index*. The mixed use index[5] was calculated based on the research conducted by Zhang et al. (2006) who quantified the level of employment-related mixed use around the residential land use. The formula used to calculated mixed index is Nf/(Nf+Nr). Nr is the total of residential land use within the TOD area and Nf is the total of functional land use other than residential within the TOD area. The mixed use index ranged from 0 to 1. Value 1 shows the highest mixed use index.

The process of calculating land used diversity level and mixed use index was depicted by the Figure 4-5.

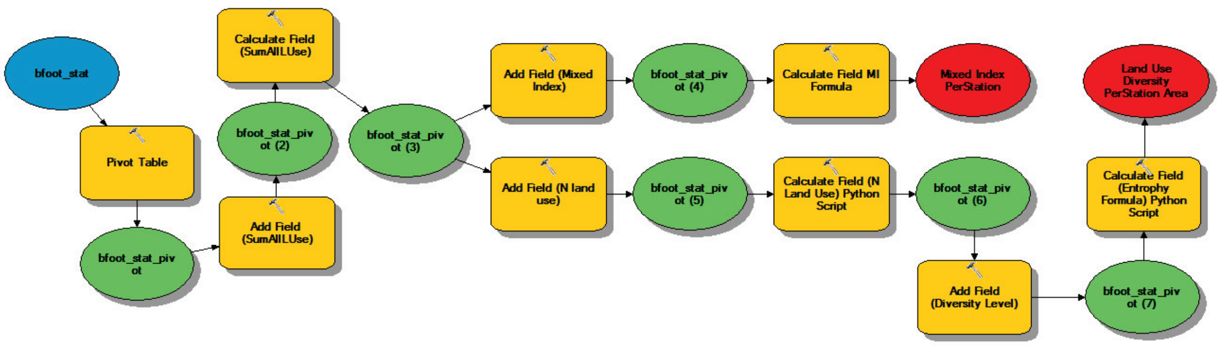


Figure 4-5 Calculation of land use diversity level and mixed index

### 4.1.3. Calculation of Walkability Indicators

There are two type of data used to calculate the indicators related to the walkability. The first one is the *road network* derived from *TOP10NL*. The road network was reclassified based on the likelihood of the roads to be used as pedestrian way. The process of road network reclassification is presented in APPENDIX B. The roads which are considered as fast traffic were removed from the network data. These removed roads are motorway *(autosnelweg),* main road *(hoofweg),* and regional road *(regionale weg)* which are categorized as fast traffic (*sneelverkeer)*. The notion of approximating the pedestrian path based on the reclassified road network was adopted from the research by Schlossberg et al. (2003).

The second source is *station* point derived from *Open Street Map (OSM)*[6]. The locations of station were verified again visually using google map. Buffers of 800 meters for TOD areas were created using these points. The indicators used to represent walkability were derived based on the work of Schlossberg et al. (2003). The first indicator is *quantity of accessible path*. This indicator is calculated based on the length of accessible road for pedestrian within each TOD area of the stations. The unit of measurement is meter. Figure 4-6 depicts the process of calculating accessible path in ArcGIS.

[5] It should be noted that mixed use index and land use diversity level are different. Both served different purposes in this study. While land use diversity level represents diversity criteria, mixed use index represents walkability criteria.
[6] Actually the data from TOP10NL also contains station point. But this station point is not complete. Data from OSM is better.

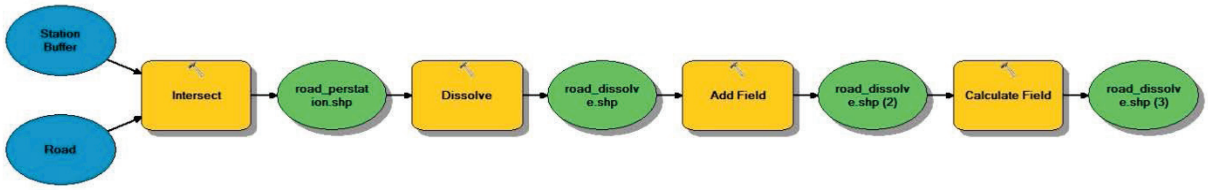


Figure 4-6 The process of calculating quantity of accessible path

The second indicator is *intersection density*. Initially, the intersection density was produced together with the dead ends density. The process was started by creating network dataset in ArcGIS using the road network. Then, intersections and dead ends were created automatically within the network data set. The Figure 4-7 shows process of separation between dead ends and intersections, and Figure 4-8 shows the resulting map. The intersection density was calculated by dividing number of intersection with the size of buffer (2.9095 km$^2$. The dead density was also calculated the same way. So the unit measurement of both indicators is number of intersections (dead ends) per square km.

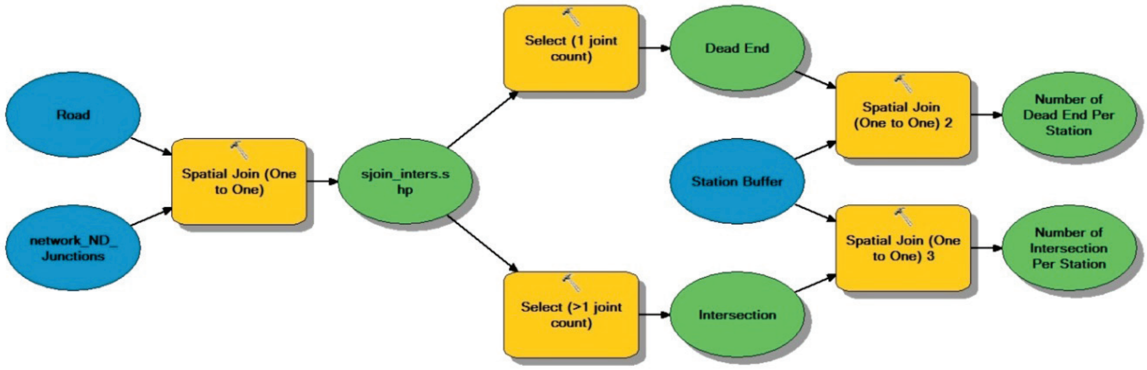


Figure 4-7 The process of producing intersections and dead ends

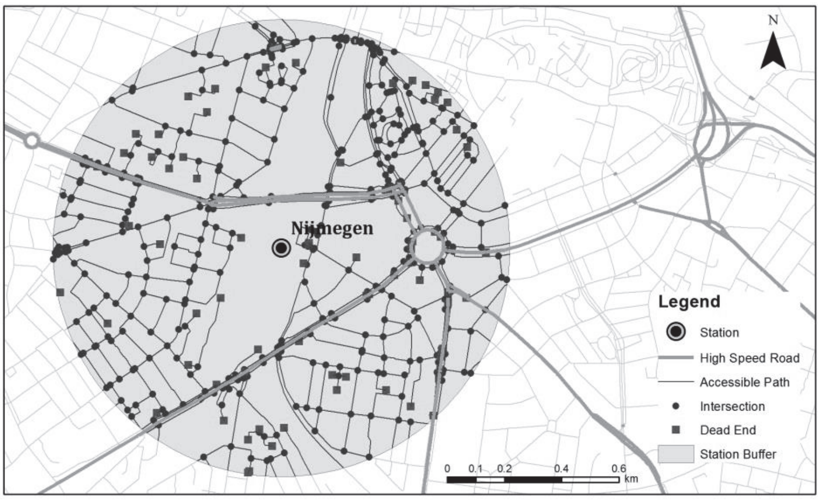


Figure 4-8 The maps of intersections and dead ends around station Nijmegen

However, the *dead ends density* was *dropped* as the indicators, because in reality dead ends were rarely present in the Netherlands generally. Some of the dead ends produced previously were also verified visually using google maps and google street views. Many dead ends were found false because apparently there are some pedestrian paths which are not recorded in the network data. The reliability of dead ends data is questionable. Hence it was excluded from indicator list.

The last indicator related to the walkability is *Impedance Pedestrian Catchment Areas (IPCA*). This indicator is based on the Pedestrian Catchment Areas (PCA) which is also known as Ped-Shed. The term "impedance" used because it was applied at the network with high speed road (impedance) removed. The catchment area was calculated based on the 800 meters of pedestrian movement along the network towards the station. The *network analyst* of '*new service area'* was performed with break value 800 meters and the movement settings towards the facilities. All of the networks were considered as two way streets since in reality the pedestrian can move in both directions. The indicator was calculated based on ratio of each catchment areas in square km compared to the whole buffer of TOD area (2.9095 $km^2$). The value of IPCA is ranged from 0 to 1. Value 1 represents the highest level of catchment area. The result of IPCA map is presented in the Figure 4-9.

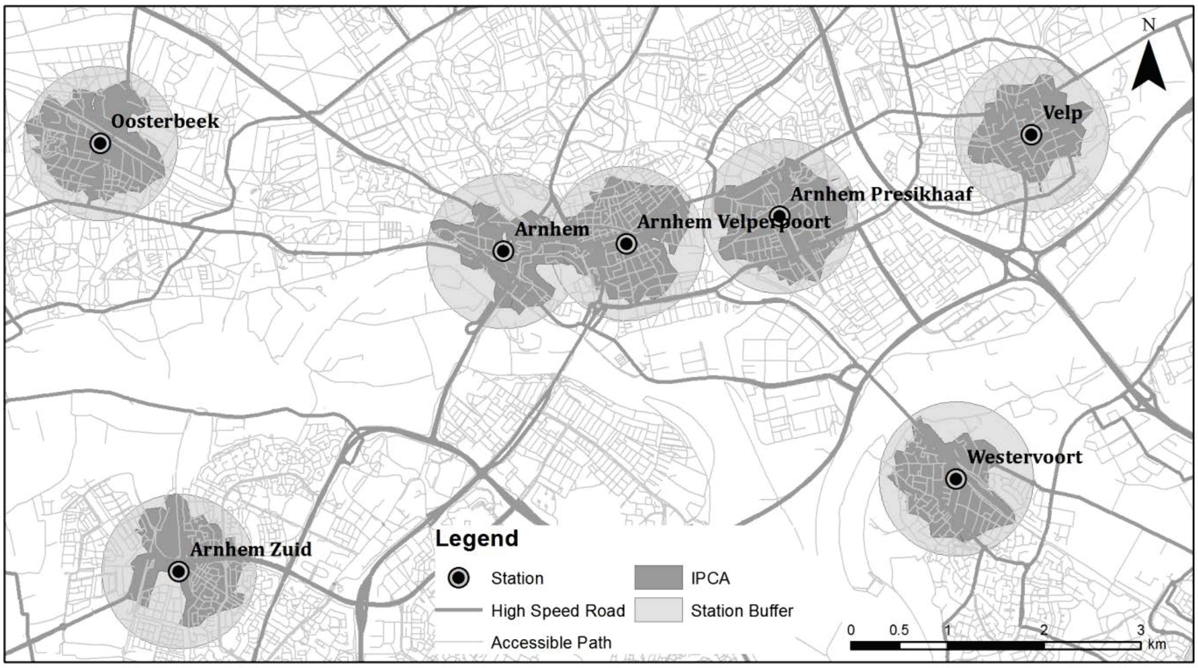


Figure 4-9 Impedance Pedestrian Catchment Area (IPCA) Map

#### 4.1.4. Calculation of Location-Accessibility Indicators

The location accessibility in this research was calculated based on *the number of jobs* that is accessible within the area of walking distance from the station. The data used for this indicator was derived from CBS 2008. It contains data of job per sector at municipality level. This municipality data was used as base unit to calculate number of jobs. The jobs were divided into four sectors e.g. (1) agricultural, forestry and fishing, (2) industrial and energy, (3) commercial, (4) non-commercial. First, the ratio between number of jobs per sector and the building footprint area ($m^2$) for each sector was calculated. Then, number of jobs per $m^2$ is derived. After that, using this figure, number of jobs within the area of walking distance around the station was calculated.

Similar with methods used when calculating density indicators, *data apportion for non-coterminous* polygons were performed. But instead of using buffer of 800 meter around station, Impedance Pedestrian Catchment Areas were used as the unit of analysis. This is because based on the notion of accessibility provided by the station. Access to job was assumed as the area of walking distance from the station which in this case, was represented by Impedance Pedestrian Catchment Areas (IPCA).

Out of four sectors of jobs mentioned earlier, only three of them were used. Jobs in agriculture, forestry and fisheries were excluded from analysis. This sector is considered less related to the means of TOD. Moreover, there is no data available about building footprints related to this sector. The number of jobs for three sectors was estimated by proportion each of building footprints per neighbourhood towards the IPCA per station. Figure 4-10 shows the process of deriving number of jobs per station for commercial sector.

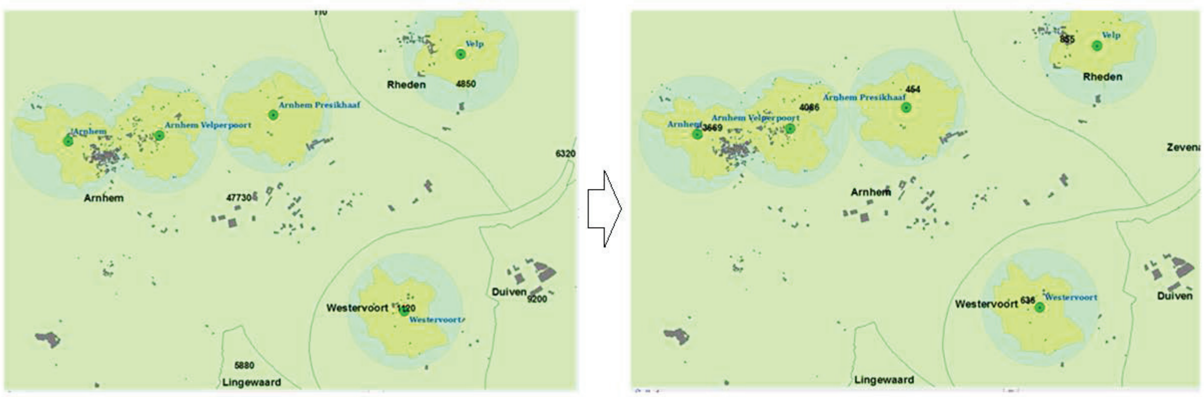


Figure 4-10 Illustration of process of deriving number of jobs accessible per station

The model used to produce number of jobs per station for commercial sector is presented in the Figure 4-11. The processes of calculating number of jobs per station for other two sectors follow the same procedure. Number of jobs is produced for each sector and the result is presented in APPENDIX B.

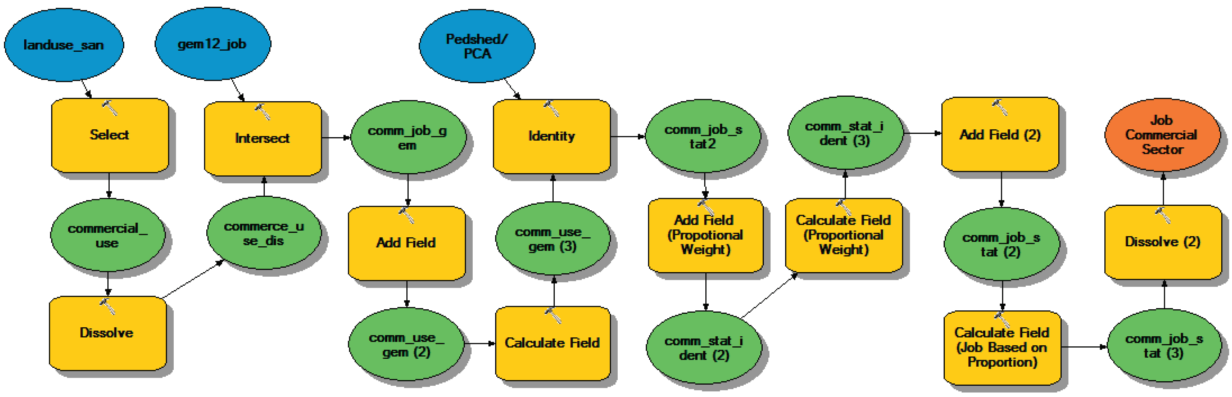


Figure 4-11 Diagram showing the process of deriving number of jobs accessible per station

#### 4.1.5. Calculation of Passenger Load

The first non-spatial indicator discussed in this part is *passenger load*. Passenger load is a measure of how loaded is the system. It is based on the *number of passenger* and the *capacity* available. The available data regarding this indicator is number of passenger in daily average. It was derived from SAN authority. We do not have the separated data between passenger in peak hours and off peak hours. Because of the limited data available regarding this indicator and the complexity of certain variables per station, several assumptions were made.

In Netherlands, there is a card called OV Chipkaart which allows people to use public transport (train, bus, tram, subway) by registering the card when do check in. The card has same function as ticket and can be recharged with money. Most of the people who regularly travel in Netherland use this card. The facilities related to this card are presented in Figure 4-12. However, there are some people who still use the paper ticket for different reason e.g. the passenger cannot use the ov chipkaart because of losing it, low balance, or the card is not valid anymore, visitor who stayed in Netherlands for few days normally would not need the card, some people might use discounted paper ticket during off-peak hours that allows travelling throughout the day with cheaper fare, etc.


Figure 4-12 OV Card and OV facilities in the station

The *passenger data* is derived from the users who register their OV Chip card to check in before using the train. So the passengers who used paper ticket are not counted. This should not be a major problem because most of people who travel regularly in Netherlands use OV Chipkaart. The research on TOD focuses on the people who use train regularly as part of their daily activities.

*First assumption* about passenger data was made to determine the peak hour. In reality, the peak hours between stations are different. However, the assumption was made based on the peak hours in the Netherlands which are between 07:00 am – 08:30 am and 4:30 pm – 6:00 pm. Then *second assumption* was applied, to get the proportion between number of passenger within peak hour and number of passenger within off-peak hour. It was estimated based on NS (Nederlandse Spoorwegen) mobile app that allows user to check level of crowdedness of the train in the station during the certain time period (Figure 4-13). The number of passenger in the peak hours was assumed as 25% of total passenger in daily average.


Figure 4-13 NS app that allows passenger to predict level of crowdedness in the train

The *capacity* of the train was calculated based on the *type of the train* which serve the stations and the *frequency of the train*. The type of the train in the Study area generally can be divided into *four* categories which are *ICE, intercity, sprinter*, and *local trains,* as shown in Figure 4-14. Each has different capacities. Actually, one type of train can be varied again based on train model and series. For Instance, Intercity series 4000 has 3 cars and capacity of 35 in 1st class and 163 in 2nd class, while Intercity series 4200 has 4 cars and capacity of 59 in 1st class and 198 in 2nd class. Moreover, there are also double-decked intercity trains with more capacities. Even, number of cars can varies as well for intercity train. Similarly, ICE, sprinter and local trains also have various capacities based on the model of the train and company who operate the trains.

The detailed of data for model of the train and number of cars of the trains which serve each stations is quite complicated and there is no data available regarding this matter. For instance, the train in station Arnhem operates from 06.00 am until 01.30 am the next day, and there are 24 trains operate here per hour. Indeed, there are different type of trains and different number of cars which operate at this hour and the next hour. More thorough observations are required to obtain such data. Therefore in this study, the most common capacities for each four general categories of the train were used, as shown on Table 4-1.


Figure 4-14 The train which operate in the SAN

Table 4-1 Capacity of the trains

| Train Type | 1st class | 2nd class | Total |
|---|---|---|---|
| ICE | | | **441** |
| Intercity | 59 | 198 | **257** |
| Sprinter | 40 | 184 | **224** |
| Local Train | 8 | 66 | **74** |

There is data available about the type of trains which serve each station per hour. Frequency of the trains is different between peak hour and off-peak hour. During the peak hour, there are more trains available. The *hours of operation* will also affect the daily capacity of the train. The information about how long the train operates daily in the certain station can be derived from the NS website.

The train which stops at the station will not be exactly at full capacity (empty). Unless the station is a terminus, there will always be passengers who keep staying on the train. There is no data available about this. Therefore, an *assumption* was made based on the observation during the field visit. For non-terminus station, the seats on the trains were assumed to be *40% occupied* when the trains stop at each station. There are two stations posed as terminus in the area, which are Station Nijmegen and Station Arnhem. Station

Nijmegen has function as terminus for sprinter, local train and some of intercity trains. Station Arnhem has function as terminus for local train and some sprinter.

The process of calculation for passenger load indicators is depicted by Figure 4-15. All of the assumptions are indicated as round shape. The table showing the detailed process of passenger load calculation is presented in APPENDIX C. In the end, the indicator is calculated based on the percentage between number of passenger and the capacity available.

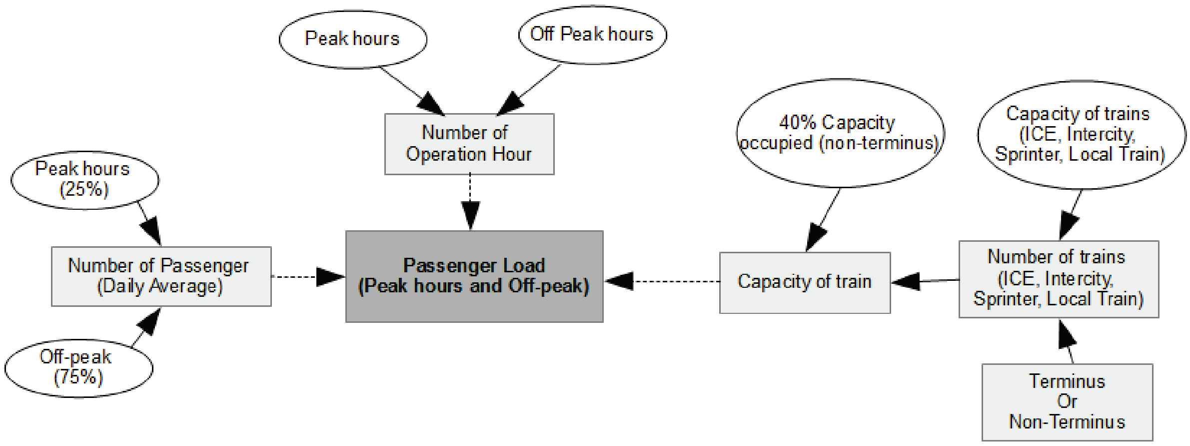


Figure 4-15 The process of passenger load calculation

#### 4.1.6. Calculation of Indicators related to the user friendliness and attractiveness

The indicators within the criteria of user friendliness and attractiveness of transit system were constructed based on the information about station facilities from the website and the observation during the *field visit* in each station. The information derived from website was also verified again during the field visit. It was found that some information on the website was obsolete and the field visit was useful to update this information. Moreover, the field visit also gave good experience about how is the ambience in the station and the built environment around the station, how easy to navigate in the station, how to plan the trip based on information and facilities available in the station, how is the condition in the train during certain time of the day, what kind of trains serve each stations, etc.

The first indicator is about *amenities*. Amenities include the presence of waiting room, benches to sit, the width of stairs, elevator, access for disabled, and ticket machine. However, this indicator was *dropped* due to the *insignificance* towards the TOD value. All the stations has the amenities mentioned before, while some of the amenities are not really relevant related to certain station e.g. elevator and stairs are not required for the stations which are on the same ground level with surrounding area.

The second indicator is about *safety*. The safety can be divided into safety in the station and safety in the train. In this research, due to limited resources and time, the only data collected is the data related to the safety in the station. Ideally the safety in the station can be indicated based on the presence of other people in the stations, the layout and design provide good visibility and good lighting in during the day, and the station should have good lighting during the night. However, some of these components are rather subjective and requires more thorough observation. Therefore, the safety was based on the following components which are feasible to observe given the time and resources available and less prone to subjectivity, which are the *presence of SOS facility* in the station, and *number of shops and restaurant* in the station[7]. The picture of both facilities is shown in Figure 4-16. SOS facility is the facility with certain buttons on it that passenger can press in case they need important information or in case of emergency. The presence of shops and restaurants, in addition to providing amenity for passenger, also can indicate the presence of other people in the station.


Figure 4-16 The SOS facility (left), shops (middle), and restaurants (right) in the station

Actually, the field visit managed to collect information about the presence of other people in the station for one certain time of day. It was found that in some station that has less train frequency of service, the station tend to be empty until 5-10 minutes towards the departure. Therefore, the presence of other people was recorded around 5 minutes before the next train schedule. However in this study, it was decided not to include this as indicators for safety because it really depends on the time of the day when the observation was conducted.


Figure 4-17 Digital information display in the station

[7] The safety indicator is given value 1 if the station has SOS facility, and the value is 0 if the station has no SOS facility. Then, this value is added with number of shops and restaurant in the station.

The third indicators, *passenger circulation*, due to data and resources available, are represented by the *presence of display system*. Typically the display system in Netherlands consists of digital display and paper display. All the stations have paper display, so this is excluded because of insignificance towards TOD value. Therefore, only digital display system was be used as indicator. There are two types of digital display included in the indicators[8]. The first one is digital display which gives information about several next train schedules in the station. It can be seen in the left picture of Figure 4-17. The second one is digital display located in each platform (spoor) which gives information about the next train schedule. It can be seen in the right picture of Figure 4-17.

#### 4.1.7. Number of Interchanges to Other Mode

This indicator looks at the interchange to other mode that available at the stations such as bus, tram, subway, etc. In the SAN, there is only bus available as interchange. Therefore, the indicator was measured on the basis of the availability of bus interchange at the station.

The indicator has three values. *Value 0* means *no bus* available in the station area. *Value 1* means there is bus stop in the station and the stop is *on-street* bus stops with typically 1-2 bus passing by the area. On-street bus stops can be just simply sign post along a sidewalk, or more complex with a larger paved area with shelter and other amenities, depending on passenger volume and available spaces (TCRP, 2003). *Value 2* means there are larger bus stops or bus terminals, serving multiple bus routes and usually located *off-street*, which is more common in the bus station that has function as terminus. The picture of both types of bus stop is depicted in Figure 4-18.

Figure 4-18 Off-street bus stop (Left) and On-street bus stop (right)

#### 4.1.8. Other Non-spatial Indicators

*Service frequency* of transit system was calculated based on the *number of train* operating in each station per hour. This data was directly provided by SAN authority.

*Number of connections* to different routes is about *number of routes* served by all of the train which pass on each station. This data was directly provided by SAN authority.

[8] The presence of display system is given value 2 if the station has both type of digital system. The value is 1 if the station has only of each type, and the value is 0 if there is no digital display available at the station.

The data about *parking utilization* was provided by authority in SAN. It was already available in *percentage* of parking utilization for each station. Therefore, this data was used directly without any additional analysis of modification.

## 4.2. Constructing Composite TOD Index

The TOD index was constructed using Multi Criteria Evaluation (MCE). MCE were used instead of Spatial Multi Criteria Evaluation (SMCE) because all of the indicators have one aggregated value for each station. Therefore, despite some of indicators were calculated spatially in GIS platform, all of the indicators in MCE platform were recognized as non-spatial indicators. MCE was performed using ILWIS 3.8.3.0 application. This software offers fast and easy index calculation with nice interface.

### 4.2.1. Standardization

The previous part discussing about indicator identification and indicator quantification, should have given clear insights about how the value of indicators contribute to the TOD level. This knowledge was used to apply the proper standardization methods for each indicator. The indicator is considered as *benefit* if the value of indicator positively contributes to the TOD level, and the indicators is considered as *cost* if the value of indicator negatively contributes to the TOD level. All except four indicators were considered as benefit and, these were standardized using *maximum* method as illustrated in Figure 4-19.

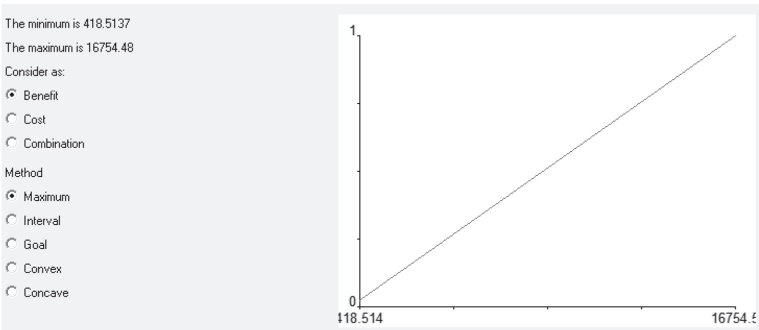


Figure 4-19 Standardization of indicators using maximum method

The *exception* was applied for *passenger load* (during peak hours and off-peak) and *utilization of parking spaces (for bicycles and car).* The passenger load was considered as *optimum* when it reaches 90%. Therefore it will pose as benefit from the value of 0 to 90. Then, it will pose as cost starting from value of 90.

The *parking utilization* also follows the same logic. Low parking utilization shows the less optimal of parking use. However, when it reaches higher values, it will pose as cost as well because it shows the sign of crowdedness. The saturated parking space is not good for TOD planning, because the TOD planning encourages more people to use transit so it will require more parking spaces as well. As indicated in Chapter 3 of this document, the optimum parking utilization in this study is 90%. The passenger load and parking utilization were considered as combination of benefit and cost and these were standardized using *goal* method, as illustrated by Figure 4-20.

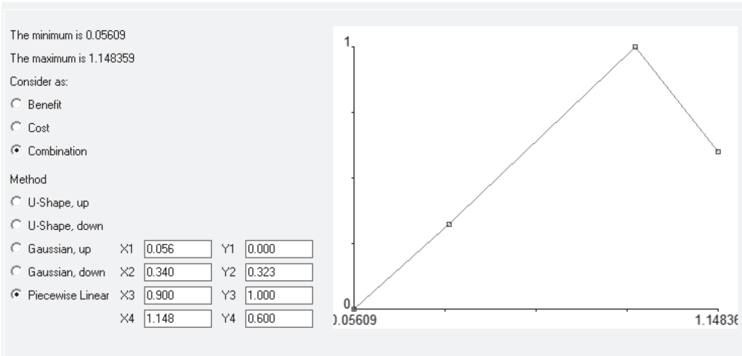


Figure 4-20 Standardization of indicator using goal method

Ideally, more detailed standardization methods for each indicator can be applied to represent better TOD level. However, these processes require more thorough literature review and empirical study. Given the resources available during this study, it was not feasible to incorporate the issues. Moreover, given the number of indicators and criteria used in this study, slight changes in indicators value as the result of different standardization applied, should not affect the final index significantly. This is examined using sensitivity analysis discussed in the next part.

Some of issues that can be considered in order to perform better standardization are described as follow.

- The shape of the curve does not have to always be linear. In case of the density indicators, one could argue that the curve should be convex as the TOD is indicated by moderate to high density development. However, it requires more thorough study to define the degree of moderate or high density.
- The intersection density is benefit for TOD in a sense that it represents the connectivity of the network. However in case of the area dominated by road for motorized vehicle, higher intersection densities can limit pedestrian movement especially when the crossing takes long time.

### 4.2.2. The Weights

The weights were derived from Stakeholder workshop. The workshop was not part of this research. It was held by Singh (2013) who worked on the same topic as this research. It was decided that the *ranking methods* would be more convenient to be used. Initially, the *pairwise method* was intended to be used. However, the internal experiment showed that this method is not preferable by the respondents.

Based on result of the stakeholder workshop, the ranks of each criteria and indicators are presented in the Table 4-2. These weights do not really conform to the concept of TOD discussed in various literatures. Many studies about TOD emphasized more in the built environment criteria especially density, diversity, and pedestrian friendly environment. However, the stakeholders in study area emphasize more on the criteria related to the transit system. Surprisingly, they put walkability criteria and diversity criteria as rank 6th and 7th respectively.

Table 4-2 The weights based on result of stakeholder workshop

| Criteria | Indicators | Ranks | Weights |
|---|---|---|---|
| Operational Capacity | | **2** | **0.19** |
| | Passenger load in peak hours | 1 | 0.67 |
| | passenger load in off peak hours | 2 | 0.33 |
| User friendliness and attractiveness of the transit | | **4** | **0.11** |
| | Safety in Transit Stop | 2 | 0.50 |
| | Information displays at station/ stop | 1 | 0.50 |
| Access to the station and from the station | | **3** | **0.15** |
| | Frequency of trains | 1 | 0.40 |
| | Interchange modes to other routes of the same mode | 2 | 0.30 |
| | Interchange to other modes | 3 | 0.20 |
| | Access to locations from station/ stop | 4 | 0.10 |
| Parking demand-supply for different modes at the station | | **5** | **0.08** |
| | Parking demand- supply for autos | 1 | 0.67 |
| | Parking demand- suuply for cycles | 2 | 0.33 |
| Density | | **3** | **0.15** |
| | Population Density | 1 | 0.67 |
| | Commercial density | 2 | 0.33 |
| Diversity | | **7** | **0.03** |
| | Land Use Diversity | 1 | 1.00 |
| Walkability and cyclability | | **6** | **0.06** |
| | Mixed land use | 4 | 0.10 |
| | Quantity accessible footpaths/ cycle paths | 1 | 0.40 |
| | Intersection density | 2 | 0.20 |
| | Ped shed area | 3 | 0.30 |
| Economic development | | **1** | **0.22** |
| | Business Density | 1 | 1.00 |

### 4.2.3. Sensitivity Analysis

Sensitivity analysis was performed to see the robustness of the model that has been produced so far. Given the amount of indicators and criteria used in this research, the weights could be prone to the uncertainties. Therefore, the sensitivity analysis is performed to see whether the slight changes in the weight would affect the TOD index in significant way.

There are 18 indicators used to produce TOD index. The ideal sensitivity analysis would demand many more combination of weight changes. However, to make things less complicated, the sensitivity analysis was performed at criteria level. First, one criterion was added up 10% of its own weight and the rest of criteria were reduced up equally based on that 10%. Then, that particular criterion was reduced up 10% of its own weight, while the rest of criteria were added up equally based on that 10%. This procedure was repeated for all the criteria until there are 16 combinations of new weights for sensitivity analysis. The combination of new weights is presented in Appendix D. The result of sensitivity analysis can be seen at the Table 5-3 Table 5-4 in the next chapter.

# 5. RESULTS AND DISCUSSIONS

## 5.1. Result of Indicator Calculation

There are 18 indicators that had been calculated for 21 stations in study area. The spatial distribution of each station was presented through Figure 1-3 in Chapter 1 of this document. Table 5-1 and Table 5-2 present the value of each indicator for all station in SAN, which had been calculated on the basis of methodology discussed in the previous chapter. Table 5-1 presents all of the criteria and indicators that are more related to the *transit system*. Table 5-2 present all of the criteria and indicators that are more related to the *built environment* around the transit system. These tables can give a good insight about how was the score of each station individually within all of the indicators and the criteria that had been used to construct the TOD index.

Table 5-1 Result of indicator calculation

| Station | Operational Capacity | | User Friendliness | | Accessibility | | | | Parking Utilization | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Passenger Load (Peak) | Passenger Load (Off-Peak) | Display System | Safety | Service Frequency | Connections | Interchange (Bus) | Location Accessibility | 4 Wheelers Utilization | Cycles Utilization |
| | *passenger per capacity in percentage* | *passenger per capacity in percentage* | *presence of digital display* | *presence of safety components* | *number of train per hour* | *number of routes* | *presence of bus stops* | *number of jobs* | *parking usage per capacity in percentage* | *parking usage per capacity in percentage* |
| Arnhem | 92.57% | 50.49% | 2 | 14 | 25 | 12 | 2 | 8122 | 60.00% | 83.90% |
| Arnhem Presikhaaf | 24.46% | 13.34% | 1 | 1 | 4 | 2 | 1 | 2867 | 77.50% | 54.60% |
| Arnhem Velperpoort | 28.59% | 17.15% | 2 | 1 | 12 | 5 | 1 | 7451 | 49.10% | 95.90% |
| Arnhem Zuid | 15.22% | 9.13% | 0 | 1 | 8 | 4 | 1 | 468 | 97.60% | 72.70% |
| Didam | 44.55% | 26.73% | 1 | 0 | 8 | 3 | 0 | 1399 | 79.70% | 67.80% |
| Dieren | 28.41% | 16.50% | 2 | 3 | 8 | 4 | 1 | 1685 | 97.10% | 73.60% |
| Duiven | 90.68% | 54.41% | 1 | 0 | 8 | 3 | 0 | 661 | 72.20% | 65.30% |
| Elst | 30.30% | 17.71% | 1 | 1 | 11 | 6 | 1 | 1178 | 81.60% | 84.20% |
| Molenhoek-Mook | 28.69% | 33.32% | 0 | 0 | 6 | 2 | 1 | 0 | 86.20% | 72.70% |
| Nijmegen | 114.84% | 65.34% | 2 | 15 | 15 | 7 | 2 | 4577 | 16.00% | 65.00% |
| Nijmegen-Lent | 5.61% | 3.37% | 1 | 1 | 4 | 4 | 1 | 549 | 98.60% | 71.60% |
| Nijmegen Dukenburg | 38.40% | 22.29% | 1 | 2 | 4 | 2 | 2 | 10483 | 78.70% | 60.90% |
| Nijmegen Heyendaal | 77.12% | 89.55% | 1 | 0 | 6 | 2 | 1 | 6631 | 98.70% | 95.30% |
| Oosterbeek | 7.47% | 8.41% | 0 | 1 | 3 | 2 | 1 | 410 | 94.10% | 43.60% |
| Rheden | 15.39% | 8.94% | 0 | 1 | 4 | 2 | 0 | 350 | 53.60% | 62.30% |
| Velp | 22.21% | 12.90% | 1 | 1 | 4 | 2 | 0 | 1227 | 72.00% | 84.70% |
| Westervoort | 11.73% | 7.04% | 0 | 0 | 8 | 3 | 1 | 984 | 63.00% | 38.70% |
| Wijchen | 58.35% | 33.88% | 1 | 2 | 4 | 2 | 1 | 4532 | 91.20% | 82.30% |
| Wolfheze | 11.78% | 13.25% | 0 | 2 | 3 | 2 | 1 | 1056 | 64.10% | 31.80% |
| Zetten-Andelst | 34.35% | 44.16% | 0 | 0 | 3 | 2 | 1 | 615 | 17.50% | 63.00% |
| Zevenaar | 109.14% | 65.48% | 1 | 2 | 8 | 3 | 1 | 916 | 99.60% | 70.90% |

As we can observed from the tables, two largest stations in SAN, station Arnhem and station Nijmegen scored relatively higher compared to other stations, especially in indicators for *first four criteria* (Table 5-1) which are more related to the *quality of transit system*. This conforms to the fact that both stations are the largest two stations of the region in terms of the size, facilities, and connections. However, both stations scores competitively with other stations in the indicators within *last four criteria* (Table 5-2) which are more related to the *built environment* around the station.

Within the criterion operational capacity, majority of the station have low passenger load. During the peak hour, there are 15 stations with passenger load less than 50%. This condition shows there are too much capacity available and indicates the waste of resources. On the other hand, there are two stations with passenger load higher than 100% during the peak hour. This indicates that during the peak hour, some of the passengers have to stand inside the train because all of the seats are occupied. Based on the indicators, the operational capacity in SAN is not optimal.

Table 5-2 Result of Indicator Calculation (2)

| Station | Density | | Diversity | Pedestrian Friendly | | | | Economic |
|---|---|---|---|---|---|---|---|---|
| | Population Density | Commercial Density | Diversity | Mixed Use Index | Path Length | Intersections | IPCA Ratio | Business Density |
| | *population per sq km* | *number of commercial activities per sq km* | *diversity index* | *mixed index* | *meters* | *number of intersection per sq km* | *IPCA per buffer of 800 m* | *Number of business activities per sq km* |
| Arnhem | 3739.75 | 514.06 | 0.29 | 0.45 | 32755 | 141.83 | 0.43 | 644.94 |
| Arnhem Presikhaaf | 3986.08 | 60.21 | 0.25 | 0.51 | 40059 | 202.54 | 0.61 | 147.30 |
| Arnhem Velperpoort | 9131.66 | 461.31 | 0.36 | 0.59 | 42019 | 196.07 | 0.60 | 647.43 |
| Arnhem Zuid | 3210.26 | 27.37 | 0.17 | 0.84 | 46448 | 215.97 | 0.48 | 50.26 |
| Didam | 2156.76 | 69.17 | 0.27 | 0.49 | 26467 | 106.49 | 0.60 | 123.91 |
| Dieren | 2279.68 | 62.20 | 0.19 | 0.58 | 25893 | 100.52 | 0.54 | 96.04 |
| Duiven | 4650.93 | 99.53 | 0.21 | 0.79 | 44149 | 211.99 | 0.64 | 78.63 |
| Elst | 1873.11 | 137.35 | 0.30 | 0.42 | 29138 | 123.41 | 0.41 | 179.15 |
| Molenhoek-Mook | 1471.52 | 0.00 | 0.05 | 0.65 | 31421 | 97.54 | 0.40 | 0.00 |
| Nijmegen | 6978.38 | 224.93 | 0.32 | 0.60 | 43111 | 213.98 | 0.46 | 312.52 |
| Nijmegen-Lent | 1065.44 | 23.89 | 0.13 | 0.60 | 16269 | 230.41 | 0.27 | 29.86 |
| Nijmegen Dukenburg | 3909.94 | 212.49 | 0.25 | 0.55 | 43355 | 225.93 | 0.59 | 258.77 |
| Nijmegen Heyendaal | 3481.48 | 74.15 | 0.30 | 0.33 | 45203 | 61.21 | 0.59 | 151.28 |
| Oosterbeek | 1940.79 | 76.64 | 0.15 | 0.72 | 36481 | 141.83 | 0.57 | 135.36 |
| Rheden | 16754.48 | 553.87 | 0.26 | 0.58 | 28048 | 93.06 | 0.59 | 893.26 |
| Velp | 3844.26 | 204.03 | 0.26 | 0.64 | 30344 | 107.99 | 0.44 | 290.62 |
| Westervoort | 6385.69 | 109.98 | 0.19 | 0.67 | 30217 | 114.46 | 0.49 | 155.26 |
| Wijchen | 3681.53 | 168.70 | 0.28 | 0.63 | 43259 | 210.00 | 0.63 | 194.58 |
| Wolfheze | 719.58 | 15.92 | 0.12 | 0.48 | 31420 | 125.90 | 0.63 | 17.42 |
| Zetten-Andelst | 418.51 | 75.14 | 0.16 | 0.25 | 13626 | 28.86 | 0.30 | 63.70 |
| Zevenaar | 1457.58 | 32.35 | 0.23 | 0.38 | 24827 | 94.55 | 0.41 | 102.51 |

In the density criterion, Station Rheden scores much higher than other stations especially in population density indicator. This is most likely caused by the fact that the most populated neighbourhood in SAN is Rheden which is located around the Station Rheden. In 2007, there are 43.950 residents who live in the Neighbourhood Rheden. For comparison, we can look at the second most populated neighbourhood, Duiven, which is settled by 17.780 residents in 2007. Another factor that contributes to the high density in Station Rheden is the presence of many building footprints in the area around this station as shown in Figure 5-1

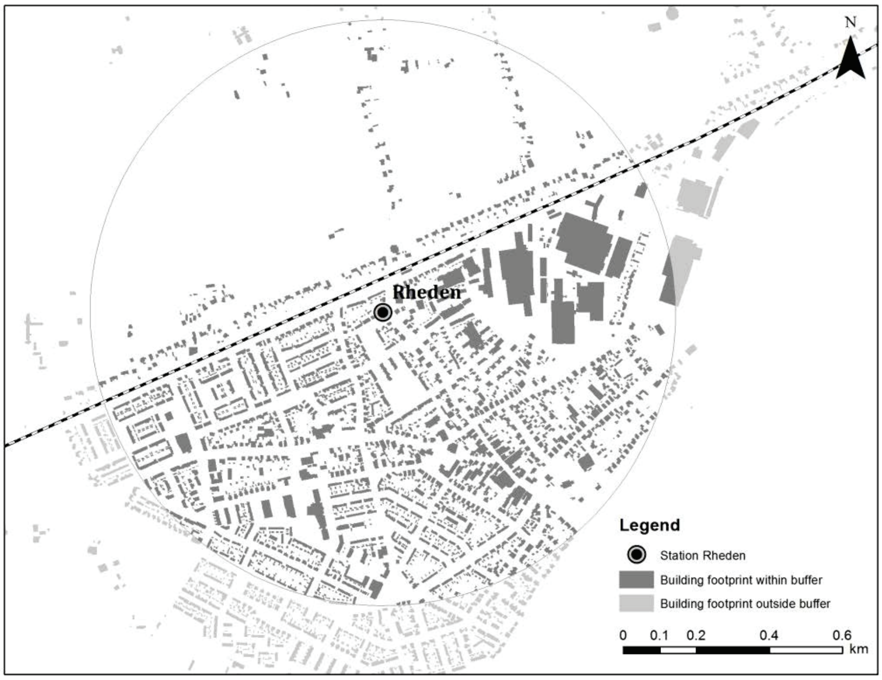


Figure 5-1 Building footprint around Station Rheden

In the land use diversity indicator, Station Arnhem Velpelpoort has the highest value. Figure 5-2 shows the map of building footprints around station Arnhem Velpelpoort that had been used to calculate the land use diversity level. Based on Figure 5-2, Station Arnhem Velperpoort has more building footprints with diverse functions within the buffers of 800 meters, compared to its neighbouring station. So, this station has high level of land use diversity indeed.

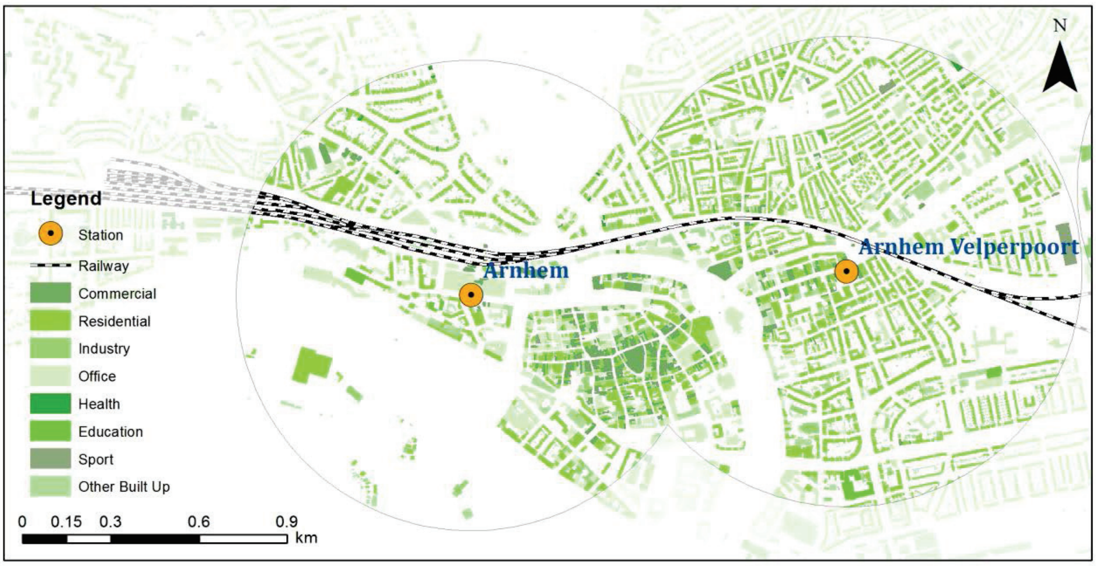


Figure 5-2 Land use diversity around Station Arnhem Velperpoort and Station Arnhem

## 5.2. TOD Index

The calculation of TOD index was conducted in ILWIS application. The ranks and weights derived from the stakeholder were incorporated into ILWIS as depicted by Figure 5-3.

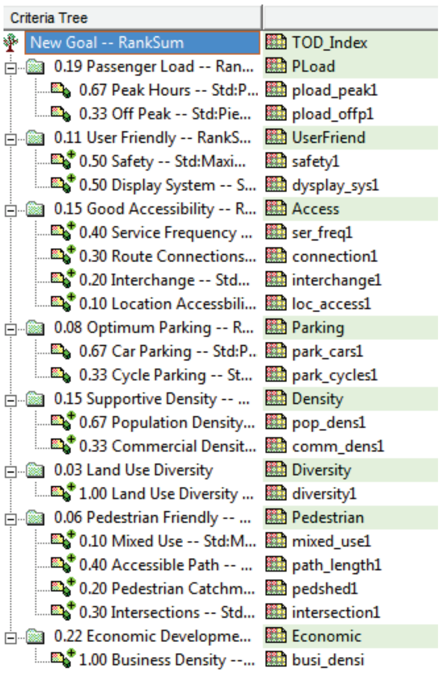


Figure 5-3 The weights used to produce TOD index in ILWIS

The process of Multi Criteria Evaluation produced one single composite index for each station in study area. TOD index for all of the station in SAN are depicted spatially in Figure 5-4.

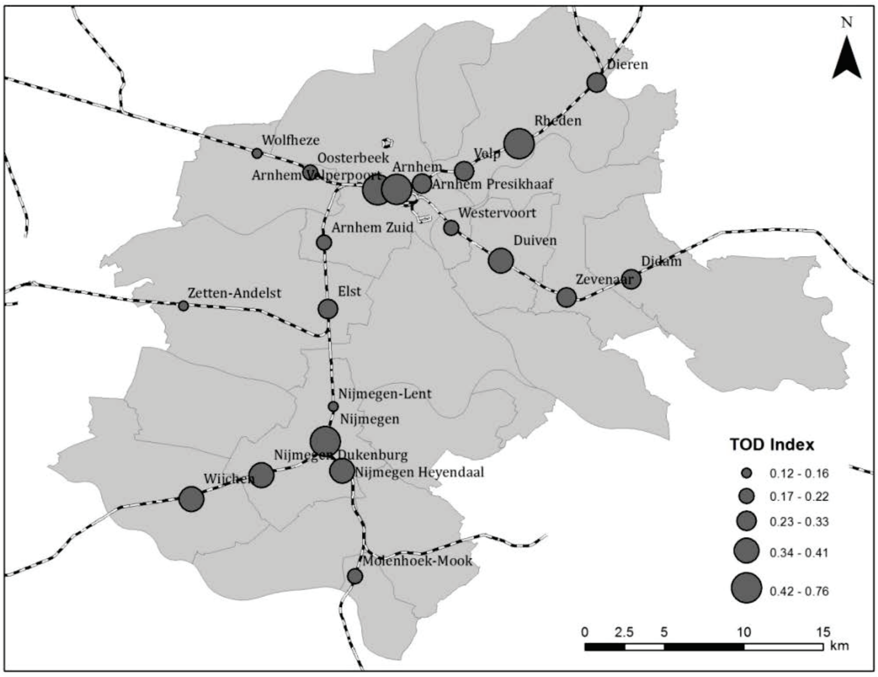


Figure 5-4 Map of TOD Index per station across the SAN

In addition to the final index, Multi Criteria Evaluation in ILWIS also produced index for each criterion. The values of each criterion are presented in Table 5-5. This table should give clear insight about the contribution of each criterion towards the final TOD index. Using this information, we can identify which aspect of the certain station that should be improved in order to reach higher TOD level. Moreover, this information also can give better understanding about the stations that has potential to be prioritized for the future development.

Table 5-3 The TOD values based on the stakeholder preferences

| Station Name | Criteria | | | | | | | Final Index | Rank |
|---|---|---|---|---|---|---|---|---|---|
| | Passenger Load | User Friendly | Access | Parking | Density | Diversity | Pedestrian | Economic | | |
| Arnhem | 0.84 | 0.97 | 0.98 | 0.69 | 0.46 | 0.82 | 0.66 | 0.72 | 0.77 | 1 |
| Arnhem Velperpoort | 0.27 | 0.53 | 0.49 | 0.59 | 0.64 | 1.00 | 0.88 | 0.72 | 0.57 | 2 |
| Nijmegen | 0.65 | 1.00 | 0.66 | 0.19 | 0.41 | 0.89 | 0.86 | 0.35 | 0.57 | 3 |
| Rheden | 0.14 | 0.03 | 0.12 | 0.50 | 1.00 | 0.72 | 0.62 | 1.00 | 0.52 | 4 |
| Nijmegen Heyendaal | 0.89 | 0.25 | 0.31 | 0.85 | 0.18 | 0.83 | 0.69 | 0.17 | 0.45 | 5 |
| Wijchen | 0.56 | 0.32 | 0.26 | 0.94 | 0.25 | 0.78 | 0.92 | 0.22 | 0.42 | 6 |
| Duiven | 0.87 | 0.25 | 0.21 | 0.69 | 0.24 | 0.60 | 0.95 | 0.09 | 0.41 | 7 |
| Nijmegen Dukenburg | 0.36 | 0.32 | 0.41 | 0.73 | 0.28 | 0.70 | 0.92 | 0.29 | 0.41 | 8 |
| Zevenaar | 0.71 | 0.32 | 0.31 | 0.75 | 0.08 | 0.65 | 0.51 | 0.11 | 0.37 | 9 |
| Elst | 0.28 | 0.28 | 0.44 | 0.89 | 0.16 | 0.83 | 0.59 | 0.20 | 0.35 | 10 |
| Dieren | 0.26 | 0.60 | 0.34 | 0.81 | 0.13 | 0.53 | 0.59 | 0.11 | 0.33 | 11 |
| Velp | 0.20 | 0.28 | 0.13 | 0.80 | 0.28 | 0.72 | 0.62 | 0.33 | 0.33 | 12 |
| Didam | 0.42 | 0.25 | 0.22 | 0.77 | 0.13 | 0.75 | 0.61 | 0.14 | 0.31 | 13 |
| Arnhem Presikhaaf | 0.22 | 0.28 | 0.24 | 0.68 | 0.19 | 0.71 | 0.86 | 0.16 | 0.30 | 14 |
| Arnhem Zuid | 0.14 | 0.03 | 0.33 | 0.79 | 0.14 | 0.47 | 0.93 | 0.06 | 0.25 | 15 |
| Westervoort | 0.11 | 0.00 | 0.31 | 0.45 | 0.32 | 0.52 | 0.64 | 0.17 | 0.24 | 16 |
| Molenhoek-Mook | 0.32 | 0.00 | 0.25 | 0.86 | 0.06 | 0.14 | 0.60 | 0.00 | 0.22 | 17 |
| Oosterbeek | 0.08 | 0.03 | 0.20 | 0.67 | 0.12 | 0.43 | 0.76 | 0.15 | 0.21 | 18 |
| Nijmegen-Lent | 0.05 | 0.28 | 0.27 | 0.77 | 0.06 | 0.37 | 0.59 | 0.03 | 0.21 | 19 |
| Zetten-Andelst | 0.40 | 0.00 | 0.20 | 0.19 | 0.06 | 0.46 | 0.28 | 0.07 | 0.18 | 20 |
| Wolfheze | 0.13 | 0.07 | 0.21 | 0.43 | 0.04 | 0.33 | 0.69 | 0.02 | 0.16 | 21 |

## 5.3. Interpretation of TOD Index

The TOD index of each station is examined this part. The contribution of each criterion and indicators were discussed and compared to suggest potential improvement for each station. The discussion starts from the station with highest rank to the station with lowest rank.

### 5.3.1. Top Three Stations

As complementary of the information derived from the Table 5-5, radar representation provides better way of comparing the criteria within each station. In this part, we looked at the top three stations in terms of TOD index (Figure 5-5). These stations are considered as stations with higher potential for TOD planning. The examination of TOD values should give understanding about what make these stations can have high TOD index and what can be suggested to improve the current TOD level.

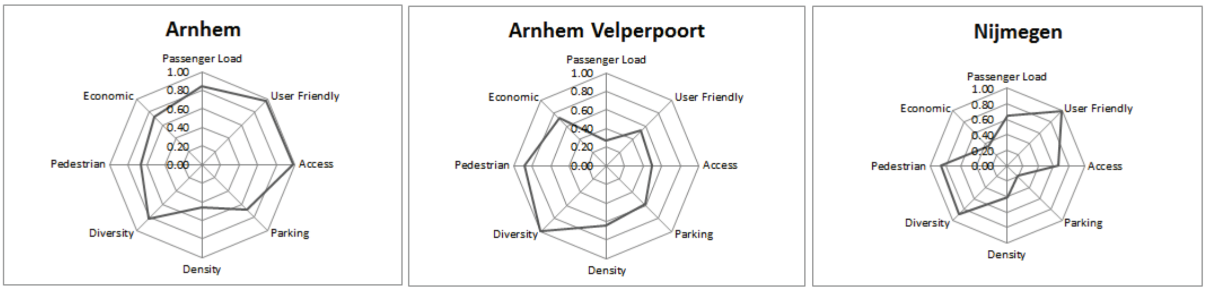


Figure 5-5 Top three station in terms of the TOD index

Generally, *Station Arnhem* as the first rank has high scores for all criteria, especially towards the criteria related to the transit system. It shows that station Arnhem have a very good transit quality that can support the TOD planning. However, compared to the other criteria, Station Arnhem has relatively low score in the criteria of density, parking, and pedestrian friendly. Thus, to improve the TOD level around the station Arnhem, one can plan to intensify the development *density* especially the population (residential) density. However, it should be noted that the improvement related to the built environment in Station Arnhem can be constrained by the availability of spaces. Figure 5-6 shows that large portion of southern and western part of Station Arnhem is dominated by water and roads. Therefore, the improvement can be focused in intensifying the current activities in northern and eastern part of the station.

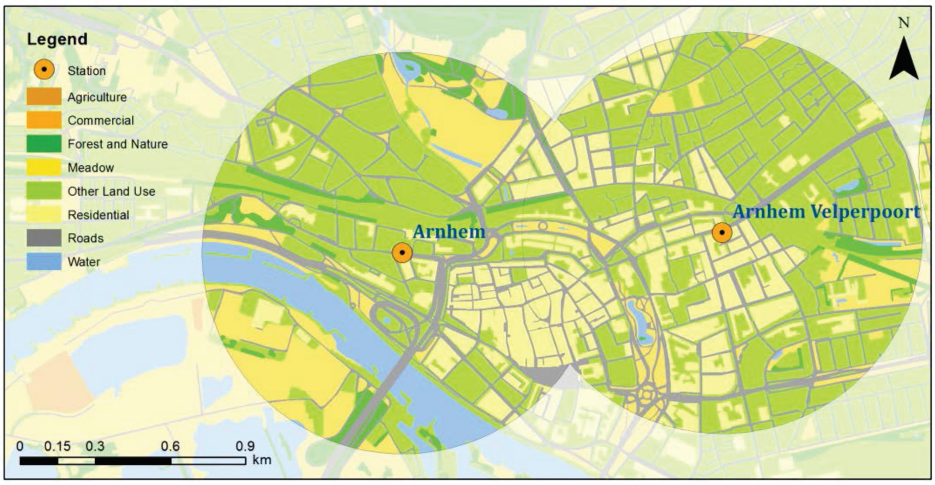


Figure 5-6 Land use map around Station Arnhem and Station Arnhem Velperpoort

Another measure can be taken as well is to optimize *parking utilization* in the train station. According to Table 5-1, Station Arnhem has quite optimum value for bicycle parking utilization and lower value in car parking utilization. Care could be taken related to the waste of space by unused car parking. This space can be used to accommodate other functions or facilities.

Another attempt to improve TOD level of Station Arnhem is by stimulating the intervention related to the *walkability indicators* such as encouraging more mixed activities. However, the intervention to walkability indicators will not contribute much towards the TOD index, since the walkability criterion was ranked as 6th by the stakeholders. The intervention towards the two former criteria will contribute more since both are ranked as 3rd (density) and 5th (parking) by the stakeholders.

Station *Arnhem Velperpoort* ranks as second with the advantages from criteria of diversity, pedestrian friendly and economic activities. It has very low scores on the passenger load criteria though. The scores for three other criteria related to the transit system (user friendly, safety, and parking) are also not really high. Basically, this station has good scores related to the built environment and activities around the station. The effort to improve the TOD levels should be focused more on the quality of transit system.

Related to the built environment indicators, TOD levels around the *Station Nijmegen* can be improved by encouraging more economic activities in the area. This will contribute significantly to the TOD level because economic criterion has the highest weight among all of the indicators. Other improvement strategies that might be effective are intensifying the development density and optimizing parking utilization in the station.

#### 5.3.2. 4th Rank to 9th Rank

Figure 5-7 shows the next six stations from fourth position to ninth position. Despite *Station Rheden* has extremely scores for the criteria related to the transit nodes, it still manages to be in the fourth highest TOD index of the region. It was because this station scored highly in the criteria economic and criteria density, which are appreciated more by the stakeholders with high weight. Basically, the improvement of TOD level for this station can be focused on the quality of transit system.

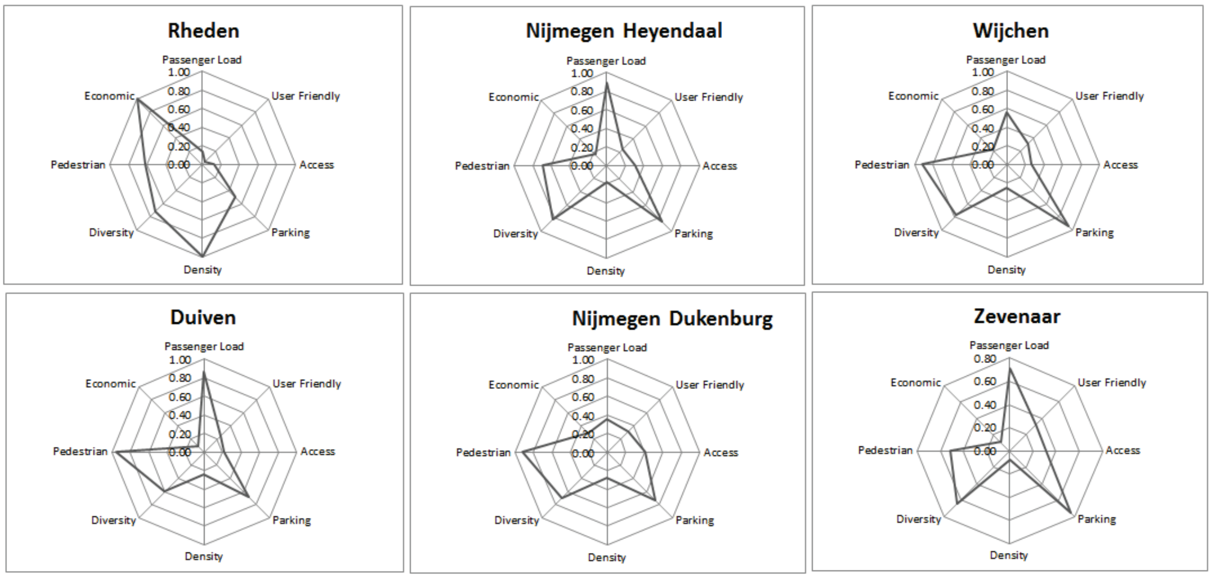


Figure 5-7 4th Rank to 9th Rank

Figure 5-7 shows that *Station Nijmegen Heyendaal, Wijchen, Duiven Nijmegen Dukenburg,* and *Zevenaar* shared relatively similar pattern. All of these stations have low scores in economic, density, user-friendliness, and access. Improvement for these stations can be concentrated in economic criterion and density criterion. It means that the plans are to encourage the intensity (density) of business activities, commercial activities, and residential development. Other attempts to increase TOD level in this station can be achieved by improving the access and user-friendliness of transit system. Specifically for Station Wijchen and Station Nijmegen Dukenburg, the improvement can be achieved through optimizing operational capacity (passenger load).

### 5.3.3. 10th Rank to 15th Rank

Based on Figure 5-8, most of the stations score relatively low in the criteria that are considered important by the stakeholders such as economic, density, passenger load, access, and user friendly. The first priority for all these stations should be improving the economic and density criteria through encouraging business activities, commercial activities and residential development. Specifically for *Station Velp, Didam* and *Arnhem Presikhaaf*, it is suggested to improve the components within criteria *access* to achieve better TOD level. As can be seen in the indicators value (Table 5-1), Station Velp and Didam do not have bus interchange in the station. Therefore, the placement of bus stop near the station should increase the access.

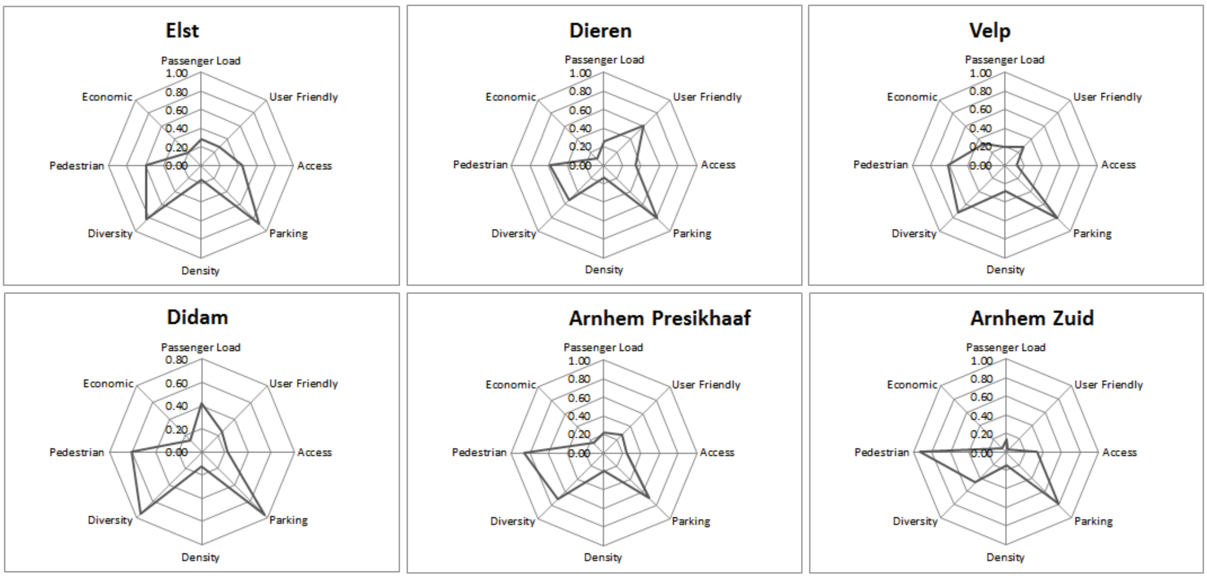


Figure 5-8 10th Rank to 15th Rank

### 5.3.4. Bottom Six Stations

Figure 5-9 shows six stations with the lowest TOD index. Most of the station within the bottom six in terms of the TOD index have moderate to high values for criteria related to the walkability. The scores of this station was drop significantly because of extremely low value in the criteria of economic development which are considered as the most important criteria by the stakeholders.

Station Molenhoek-Mook, Oosterbeek, Nijmegen Lent, and Wolfheze shared relatively similar pattern. These stations have good scores related to the criteria parking and pedestrian friendly. To improve the TOD level in addition to encouraging economic activities, much more effort should be spent on the improving the quality of transit system (user-friendliness, access and passenger load), and intensifying the density. Station *Zetten-Andelst* has good scores in the land use diversity and passenger load. Improvement suggested for this station are encouraging the economic development, improving the user-friendliness of transit system and intensifying development density in the area.

*Station Westervoort* has extremely low scores in economic, passenger load, and user-friendliness criteria. Thus the improvement for this station can be focused on the components within these three criteria, such as encouraging business activities in the area around station, providing the digital information display system in the station, and providing facilities related to the user safety in the station.

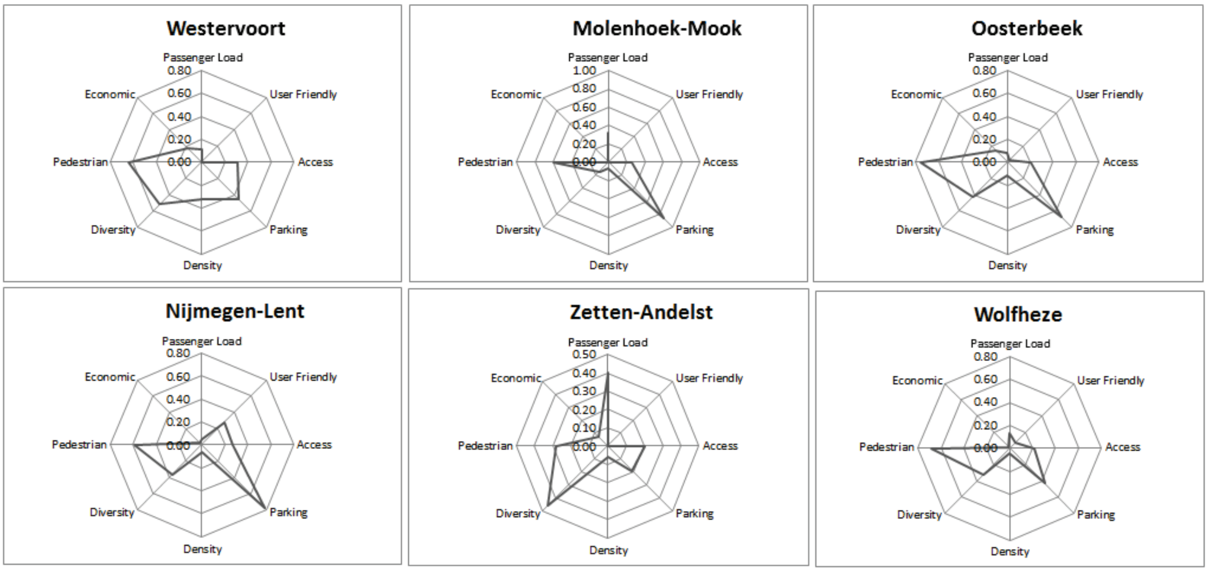


Figure 5-9 Bottom four station in term of the TOD index

## 5.4. Result of Sensitivity Analysis

The *base* weights used in sensitivity analysis is the weights that had been used to calculate the TOD index. On the basis of these *base* weights, sensitivity analysis was performed. The weights were changed ±10% for each criterion. Therefore, there are 16 combinations of weights. Table 5-3 and Table 5-4 show the result of TOD index and station ranks produced based on 16 combination change of weights.

Table 5-4 TOD Index and station ranks based on the change of weights in the criteria

| Station Name | Base | | Pload+ | | Pload- | | UserF+ | | UserF- | | Access+ | | Access- | | Parking+ | | Parking- | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank |
| Arnhem | 0.7681 | 1 | 0.7697 | 1 | 0.7664 | 1 | 0.7706 | 1 | 0.7655 | 1 | 0.7718 | 1 | 0.7643 | 1 | 0.7673 | 1 | 0.7688 | 1 |
| Arnhem Velperpoort | 0.5699 | 2 | 0.5616 | 3 | 0.5781 | 2 | 0.5685 | 3 | 0.5713 | 2 | 0.5672 | 3 | 0.5725 | 2 | 0.5694 | 2 | 0.5703 | 3 |
| Nijmegen | 0.5671 | 3 | 0.5676 | 2 | 0.5666 | 3 | 0.5718 | 2 | 0.5623 | 3 | 0.5677 | 2 | 0.5665 | 3 | 0.5629 | 3 | 0.5712 | 2 |
| Rheden | 0.5200 | 4 | 0.5116 | 4 | 0.5284 | 4 | 0.5138 | 4 | 0.5262 | 4 | 0.5131 | 4 | 0.5269 | 4 | 0.5198 | 4 | 0.5202 | 4 |
| Nijmegen Heyendaal | 0.4457 | 5 | 0.4539 | 5 | 0.4375 | 5 | 0.4422 | 5 | 0.4491 | 5 | 0.4420 | 5 | 0.4494 | 5 | 0.4488 | 5 | 0.4426 | 5 |
| Wijchen | 0.4224 | 6 | 0.4230 | 6 | 0.4217 | 6 | 0.4197 | 6 | 0.4250 | 6 | 0.4176 | 6 | 0.4271 | 6 | 0.4263 | 6 | 0.4185 | 6 |
| Duiven | 0.4126 | 7 | 0.4211 | 7 | 0.4041 | 8 | 0.4096 | 7 | 0.4157 | 7 | 0.4078 | 7 | 0.4175 | 7 | 0.4146 | 7 | 0.4107 | 7 |
| Nijmegen Dukenburg | 0.4068 | 8 | 0.4037 | 8 | 0.4099 | 7 | 0.4045 | 8 | 0.4091 | 8 | 0.4052 | 8 | 0.4084 | 8 | 0.4090 | 8 | 0.4046 | 8 |
| Zevenaar | 0.3665 | 9 | 0.3727 | 9 | 0.3603 | 9 | 0.3651 | 9 | 0.3679 | 9 | 0.3644 | 9 | 0.3686 | 9 | 0.3696 | 9 | 0.3635 | 9 |
| Elst | 0.3517 | 10 | 0.3477 | 10 | 0.3556 | 10 | 0.3494 | 10 | 0.3539 | 10 | 0.3513 | 10 | 0.3520 | 10 | 0.3558 | 10 | 0.3476 | 10 |
| Dieren | 0.3285 | 11 | 0.3249 | 11 | 0.3321 | 11 | 0.3307 | 11 | 0.3262 | 12 | 0.3271 | 11 | 0.3299 | 12 | 0.3322 | 11 | 0.3248 | 11 |
| Velp | 0.3271 | 12 | 0.3222 | 12 | 0.3320 | 12 | 0.3253 | 12 | 0.3289 | 11 | 0.3220 | 12 | 0.3321 | 11 | 0.3307 | 12 | 0.3235 | 12 |
| Didam | 0.3129 | 13 | 0.3131 | 13 | 0.3127 | 13 | 0.3109 | 13 | 0.3150 | 13 | 0.3096 | 13 | 0.3163 | 13 | 0.3163 | 13 | 0.3095 | 13 |
| Arnhem Presikhaaf | 0.2993 | 14 | 0.2949 | 14 | 0.3037 | 14 | 0.2976 | 14 | 0.3011 | 14 | 0.2962 | 14 | 0.3024 | 14 | 0.3018 | 14 | 0.2968 | 14 |
| Arnhem Zuid | 0.2463 | 15 | 0.2413 | 15 | 0.2512 | 15 | 0.2420 | 15 | 0.2505 | 15 | 0.2457 | 15 | 0.2468 | 15 | 0.2503 | 15 | 0.2422 | 15 |
| Westervoort | 0.2429 | 16 | 0.2384 | 16 | 0.2475 | 16 | 0.2389 | 16 | 0.2469 | 16 | 0.2428 | 16 | 0.2430 | 16 | 0.2442 | 16 | 0.2416 | 16 |
| Molenhoek-Mook | 0.2185 | 17 | 0.2194 | 17 | 0.2176 | 17 | 0.2149 | 17 | 0.2220 | 17 | 0.2180 | 17 | 0.2190 | 17 | 0.2240 | 17 | 0.2129 | 17 |
| Oosterbeek | 0.2111 | 18 | 0.2061 | 18 | 0.2161 | 18 | 0.2076 | 18 | 0.2146 | 18 | 0.2093 | 18 | 0.2129 | 18 | 0.2146 | 18 | 0.2076 | 18 |
| Nijmegen-Lent | 0.2051 | 19 | 0.1995 | 19 | 0.2108 | 19 | 0.2049 | 19 | 0.2054 | 19 | 0.2046 | 19 | 0.2057 | 19 | 0.2096 | 19 | 0.2007 | 19 |
| Zetten-Andelst | 0.1772 | 20 | 0.1815 | 20 | 0.1729 | 20 | 0.1746 | 20 | 0.1799 | 20 | 0.1771 | 20 | 0.1774 | 20 | 0.1771 | 20 | 0.1774 | 20 |
| Wolfheze | 0.1590 | 21 | 0.1566 | 21 | 0.1615 | 21 | 0.1569 | 21 | 0.1612 | 21 | 0.1585 | 21 | 0.1596 | 21 | 0.1608 | 21 | 0.1572 | 21 |

Table 5-5 TOD Index and station ranks based on the change of weight in the criteria (2)

| Station Name | Density+ | | Density- | | Diversity+ | | Diversity- | | Pedestrian+ | | Pedestrian- | | Economic+ | | Economic- | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank | Index | Rank |
| Arnhem | 0.7627 | 1 | 0.7734 | 1 | 0.7682 | 1 | 0.7679 | 1 | 0.7674 | 1 | 0.7687 | 1 | 0.7668 | 1 | 0.7693 | 1 |
| Arnhem Velperpoort | 0.5699 | 2 | 0.5699 | 3 | 0.5710 | 2 | 0.5687 | 2 | 0.5714 | 2 | 0.5683 | 2 | 0.5719 | 2 | 0.5678 | 3 |
| Nijmegen | 0.5633 | 3 | 0.5709 | 2 | 0.5679 | 3 | 0.5662 | 3 | 0.5686 | 3 | 0.5656 | 3 | 0.5601 | 3 | 0.5741 | 2 |
| Rheden | 0.5284 | 4 | 0.5116 | 4 | 0.5206 | 4 | 0.5194 | 4 | 0.5207 | 4 | 0.5193 | 4 | 0.5323 | 4 | 0.5077 | 4 |
| Nijmegen Heyendaal | 0.4397 | 5 | 0.4517 | 5 | 0.4467 | 5 | 0.4447 | 5 | 0.4468 | 5 | 0.4446 | 5 | 0.4368 | 5 | 0.4546 | 5 |
| Wijchen | 0.4175 | 6 | 0.4273 | 6 | 0.4232 | 6 | 0.4216 | 6 | 0.4248 | 6 | 0.4199 | 6 | 0.4145 | 6 | 0.4303 | 6 |
| Duiven | 0.4083 | 7 | 0.4170 | 7 | 0.4130 | 7 | 0.4123 | 7 | 0.4156 | 7 | 0.4097 | 7 | 0.4025 | 7 | 0.4227 | 7 |
| Nijmegen Dukenburg | 0.4029 | 8 | 0.4107 | 8 | 0.4074 | 8 | 0.4062 | 8 | 0.4095 | 8 | 0.4041 | 8 | 0.4014 | 8 | 0.4122 | 8 |
| Zevenaar | 0.3604 | 9 | 0.3726 | 9 | 0.3672 | 9 | 0.3658 | 9 | 0.3670 | 9 | 0.3660 | 9 | 0.3584 | 9 | 0.3747 | 9 |
| Elst | 0.3465 | 10 | 0.3569 | 10 | 0.3528 | 10 | 0.3505 | 10 | 0.3525 | 10 | 0.3508 | 10 | 0.3451 | 10 | 0.3582 | 10 |
| Dieren | 0.3234 | 12 | 0.3336 | 11 | 0.3288 | 11 | 0.3281 | 11 | 0.3295 | 11 | 0.3274 | 11 | 0.3206 | 12 | 0.3364 | 11 |
| Velp | 0.3246 | 11 | 0.3295 | 12 | 0.3280 | 12 | 0.3261 | 12 | 0.3284 | 12 | 0.3258 | 12 | 0.3248 | 11 | 0.3294 | 12 |
| Didam | 0.3080 | 13 | 0.3178 | 13 | 0.3140 | 13 | 0.3118 | 13 | 0.3142 | 13 | 0.3117 | 13 | 0.3060 | 13 | 0.3198 | 13 |
| Arnhem Presikhaaf | 0.2953 | 14 | 0.3033 | 14 | 0.3002 | 14 | 0.2984 | 14 | 0.3021 | 14 | 0.2965 | 14 | 0.2928 | 14 | 0.3058 | 14 |
| Arnhem Zuid | 0.2424 | 16 | 0.2501 | 15 | 0.2466 | 15 | 0.2459 | 15 | 0.2499 | 15 | 0.2426 | 15 | 0.2386 | 16 | 0.2539 | 15 |
| Westervoort | 0.2430 | 15 | 0.2428 | 16 | 0.2436 | 16 | 0.2423 | 16 | 0.2450 | 16 | 0.2409 | 16 | 0.2392 | 15 | 0.2466 | 16 |
| Molenhoek-Mook | 0.2147 | 17 | 0.2223 | 17 | 0.2180 | 17 | 0.2189 | 17 | 0.2205 | 17 | 0.2164 | 17 | 0.2114 | 17 | 0.2256 | 17 |
| Oosterbeek | 0.2079 | 18 | 0.2143 | 18 | 0.2115 | 18 | 0.2107 | 18 | 0.2140 | 18 | 0.2082 | 18 | 0.2072 | 18 | 0.2150 | 18 |
| Nijmegen-Lent | 0.2009 | 19 | 0.2094 | 19 | 0.2054 | 19 | 0.2049 | 19 | 0.2070 | 19 | 0.2033 | 19 | 0.1982 | 19 | 0.2121 | 19 |
| Zetten-Andelst | 0.1746 | 20 | 0.1798 | 20 | 0.1780 | 20 | 0.1764 | 20 | 0.1777 | 20 | 0.1768 | 20 | 0.1737 | 20 | 0.1807 | 20 |
| Wolfheze | 0.1555 | 21 | 0.1625 | 21 | 0.1593 | 21 | 0.1587 | 21 | 0.1619 | 21 | 0.1562 | 21 | 0.1534 | 21 | 0.1646 | 21 |

As we can see from the foregoing tables, the change of weights only slightly affects the TOD index. Thus, there was hardly any rank reversal for the stations within all 16 conditions. In some cases, rank reversals were only happened slightly at one level rank, meaning that the station can only goes up one level above or goes down one level below. The most often rank reversals are the reversal between rank 2nd (Arnhem Velperpoort) and rank 3rd (Nijmegen), which occur 6 times out of 16 conditions. The second most often rank reversals is between rank 11th (Dieren) and rank 12th (Velp), which occurs four times.

The changes of criteria that give the larger impacts to rank reversal are the increased 10% for economic criteria and the increased 10% in density criteria. Both cases resulted two rank reversal e.g. between rank 11th and 12th, and between rank 15th and 16th. This condition conform the fact that economic criteria was weighted as rank 1st and density criteria was weighted as rank 3rd by the stakeholders. So the change in these two criteria should give more impact compared to other criteria with less weight.

The *result* of sensitivity analysis above indicates that the 10% of change from the criteria weights would *not affect* the TOD index *significantly*. The effect only influenced slight change of ranks of station with small difference of TOD index. Indeed, the 10% change of indicators weights will have less significant impact, since the effect of indicator weight is less than criteria weight. Thus, this justifies why the sensitivity analysis was performed at criteria level, not at indicators level. As long as the weights of criteria do not deviate more than 10% of its weights, the TOD index will not be affected significantly.

# 6. CONCLUSION AND RECOMMENDATION

This study managed to identify the criteria indicators for measuring the TOD index based on top-down approach. This approach allows a comprehensive way of incorporating important aspect of TOD in measuring existing TOD level. Thorough literature review related to the criteria and the indicators gave a good insight about how important each indicator is for the attainment of TOD. However, the stakeholder preference expressed different views on the concept. While the literature study suggested diversity and pedestrian friendly environment as key aspects of TOD, the stakeholders consider these components as less important. For further research, the stakeholder workshop should be conducted more carefully with the more representative attendants, because this plays a crucial part in the construction of TOD index.

Generally, the indicators were categorized into spatial and non-spatial indicators. There are 25 indicators ideally used to calculate the TOD index in this study. However, due to limitation of data, time and energy resources available, only 18 indicators were quantified further. For the same reasons, some indicators were also had to be modified, so they became less precise than their initial purpose. For instance, the data available about passenger load is only about number of passenger in daily average without any differentiation between peak hours and off-peak. Thus, many assumptions were made to calculate the number of passenger in peak hours and off-peak, and some assumptions were also applied to calculate the capacities. For further study, more complete data should be collected in order to avoid making too many assumptions in the calculation.

The calculation of density indicators, mixed use level, and land use diversity relies largely in the data of building footprints. Data of building footprints does not contain information about number of floor. Therefore in this study, all of the buildings were assumed as one floor buildings. Ideally, the calculation should incorporate number of floor per building.

The calculation of indicators related to pedestrian friendly environment was conducted based on the street network data. The street network was reclassified to approximate the pedestrian paths. If the *actual* pedestrian path data is available, indeed it will give better representation of the walkability indicators. Schlossberg et al. (2003) proposed *sidewalk modelling* to refined the pedestrian path data. Furthermore, the '*design factor*' was not incorporated in the walkability indicators. If the time and resources allow, the design factor such as sidewalk width, the presence of street trees, and other pedestrian-oriented amenities, should be incorporated as walkability indicators (Schlossberg et al., 2003).

The walkable limit around the station was defined as *800 meters* based on the suggestion from SAN authority. It plays significant role towards the calculation the value of spatial indicators that employs the buffer size of station in the process. It should be noted that the walkable limit is not uniform in all the places. For example, in the context of American Cities, Calthorpe (1993) defined the walking distance as 2000 feet (609.6 meters). So, for the study of TOD in different city, it is important to define proper walking distance based on its own context.

GIS platform had been useful in process of quantification spatial indicators. Adapting the indicators calculation into GIS model can accelerate the process, especially when the similar process had to be performed repeatedly. GIS is also a powerful to combine the process of spatial analysis and mathematical formula's calculation. The calculation of entropy formula which represents both processes was successfully conducted within the GIS environment.

Moreover, with the aid of Multi Criteria Evaluation (MCE), it complements the processes of constructing the TOD index. Given the numbers of indicators and criteria used in this study, *rank* methods was considered better compared to other methods of weighting (*direct* and *pairwise*). This method is preferable based on the stakeholder convenience.

Most of the indicators were standardized as benefit in MCE. There are four indicators which will be saturated at certain point, were standardized as combination of benefit and cost. More thorough study of the indicators is required to refine the standardization methods used in this research. The standardization curve used in this research is the linear curve. However, with more focused study about each indicator, it is possible that other curve (convex, concave or U-shape) might be more suitable.

Since the methods of weighting in this research were prone to uncertainty. The sensitivity analysis was performed by changing 10% of the input parameter (criteria). Apparently, the sensitivity analysis exhibits hardly any changes in the output. This indicates that the TOD index will not easily change if there is slight change within the weights of criteria and indicators.

TOD index had been useful to support the process of TOD planning. The composition of TOD value can be easily seen in Multi Criteria Evaluation tool. The transparency of TOD values gives clear insights about the contribution of each criteria and indicators towards the final TOD index. Various forms of improvement for each station were suggested on the basis of TOD values. Generally the improvement was suggested for the criteria with high weight such as economic criterion and density criterion.

Especially for the two largest stations in the region, Arnhem and Nijmegen, the focus of improvements are different from each other.  TOD level around Station Arnhem can be enhanced more by improving the quality of built environment surrounding the station, while the Station Nijmegen can be improved by focusing on the economic development, intensifying development density, and manage more optimum parking utilization. For the station with very low TOD index, the improvement can be achieved through investing more in encouraging economic activities and the quality improvement of transit system.

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# APPENDIX A: LIST OF INDICATORS SUGGESTED BY SINGH (2013)

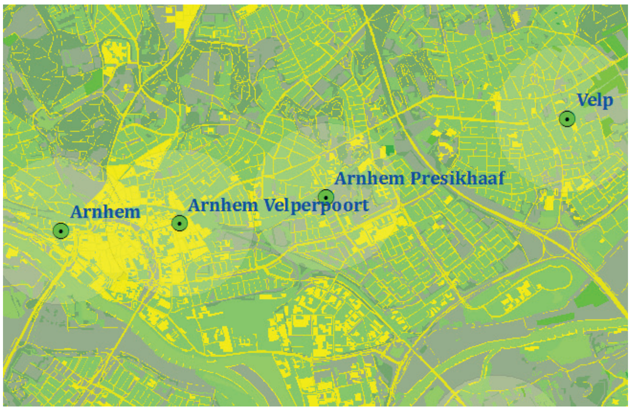
List of indicators to measure TOD level based on Singh (2013).

| Questions (Criteria) | Indicators |
|---|---|
| 1. What is the current utilization of transit nodes? | 1. Passenger load in peak hours<br>2. Passenger load in offf-peak hours |
| 2. How user friendly or attractive is the transit system? | 3. Service frequency LOS of transit service<br>4. Safety in transit<br>5. Safety of commuters at the stop/station<br>6. Information and ticketing systems |
| 3. How accessible is the transit node and what level of accessibility is provided by the node? | 7. Interchange to other modes of public transport<br>8. Access to the station/stop<br>9. Pedestrian access<br>10.Location-accessibility provided by the station/stop<br>11.Connections to different routes (LOS of transit service) |
| 4. What is the parking supply at station/stop for all modes? | 12.Parking supply-demand for cars/four wheelers<br>13.Parking supply-demand for cycles<br>14.Reserved Car Parking for special commuter groups |
| 5. What are the various densities in catchment areas? | 15.Residential density in TOD area<br>16.Employment density in TOD area<br>17.Commercial intensity/density in TOD area |
| 6. What is the level of mixed use in catchment area? | 18.Diversity of land uses |
| 7. How walkable and safe is the TOD area? | 19.Level of mixed-ness of land uses<br>20.Quality and suitablity of streetscape for walking and cycling<br>21.Density of signalled intersections/street crossings |
| 8. What is the current level of economic development in the area? | 22.Private investment of zone<br>23.Number of service/retail establishments<br>24.Tax earnings of municipality<br>25.Unemployment levels |

# APPENDIX B: QUANTIFICATION OF SPATIAL INDICATORS

## Calculation of Density Indicators

The source of land use data: Building Footprints (Left) and SAN Topography (Right).


The process of Land Use Reclassification:

**SAN Topography**
**Whole Region**

| Landuse | Count | Reclassification |
|---|---|---|
| Agriculture | 6278 | Agriculture |
| Cemetery | 209 | Other Land Use |
| Constructed/House Block | 495 | Residential |
| Crib | 836 | Other Land Use |
| Cycle path | 3981 | Roads |
| Forest | 15815 | Forest |
| Free way | 1291 | Roads |
| Large building | 1373 | Residential |
| meadow | 22888 | Meadow |
| Mixed forest | 4708 | Forest |
| Nature | 935 | Nature |
| Other landuse | 22214 | Other Land Use |
| Parking | 500 | Other Land Use |
| Pedestrian | 26 | Roads |
| Roads | 11664 | Roads |
| Sand | 318 | Sand |
| Stores | 580 | Commercial |
| Water | 3848 | Water |

**Building Foot prints**
**Whole Region**

| GEBR_DOEL1 | | Count | Reclassification |
|---|---|---|---|
| Others | Others | 173197 | Other Built Up |
| bijeenkomstfunctie | assembly function | 1858 | Office |
| celfunctie | cell function | 4 | Other Built Up |
| gezondheidszorgfunctie | health care function | 573 | Health |
| industriefunctie | industry function | 4864 | Industry |
| kantoorfunctie | office function | 2264 | Office |
| logiesfunctie | hotel/inn function | 1290 | Commercial |
| onderwijsfunctie | educational function | 540 | Education |
| overigegebruiksfunctie | other functional | 13474 | Other Built Up |
| sportfunctie | sports function | 349 | Sport |
| winkelfunctie | shopping function | 2367 | Commercial |
| woonfunctie | residential function | 245086 | Residential |

The ArcGIS python script used in the Field Calculator to reclassify the building footprints:

```
def classify(GEBR_DOEL1) :

  if (GEBR_DOEL1 ==  " " or GEBR_DOEL1 ==  "celfunctie"  or GEBR_DOEL1 ==  "overigegebruiksfunctie") :
    return "Other Built Up"

  elif (GEBR_DOEL1 ==  "bijeenkomstfunctie" or GEBR_DOEL1 ==  "kantoorfunctie") :
    return "Office"

  elif (GEBR_DOEL1 ==  "gezondheidszorgfunctie") :
    return "Health"

  elif (GEBR_DOEL1 ==  "industriefunctie") :
    return "Industry"

  elif (GEBR_DOEL1 ==  "logiesfunctie") :
    return "Accomodation"

  elif (GEBR_DOEL1 ==  "sportfunctie") :
    return "Sport"

  elif (GEBR_DOEL1 ==  "onderwijsfunctie") :
    return "Education"

  elif (GEBR_DOEL1 ==  "winkelfunctie") :
    return "Commercial"

  elif (GEBR_DOEL1 ==  "woonfunctie") :
    return "Residential"

  else :
    return "null"

classify(!GEBR_DOEL1!)
```

ArcGIS Python script used t to calculate land use diversity level: pre-logic in field calculator.

```
def Acc(Accomodation, sum_luse) :
 if (Accomodation == 0) :
  return 0
 else :
  return ( Accomodation/sum_luse)* (math.log( Accomodation/sum_luse))

def Com(Commercial, sum_luse) :
 if (Commercial == 0) :
  return 0
 else :
  return ( Commercial/sum_luse)* (math.log( Commercial/sum_luse))

def Edu(Education, sum_luse) :
 if (Education == 0) :
  return 0
 else :
  return ( Education/sum_luse)* (math.log( Education/sum_luse))

def Hea(Health, sum_luse) :
 if (Health == 0) :
  return 0
 else :
  return ( Health/sum_luse)* (math.log( Health/sum_luse))

def Ind(Industry, sum_luse) :
 if (Industry == 0) :
  return 0
 else :
  return ( Industry/sum_luse)* (math.log( Industry/sum_luse))

def Off(Office, sum_luse) :
 if (Office == 0) :
  return 0
 else :
  return ( Office/sum_luse)* (math.log( Office/sum_luse))

def Oth(Other_Built_Up, sum_luse) :
 if (Other_Built_Up == 0) :
  return 0
 else :
  return ( Other_Built_Up/sum_luse)* (math.log( Other_Built_Up/sum_luse))

def Res(Residential, sum_luse) :
 if (Residential == 0) :
  return 0
 else :
  return ( Residential/sum_luse)* (math.log( Residential/sum_luse))

def Spo(Sport, sum_luse) :
 if (Sport == 0) :
  return 0
 else :
  return ( Sport/sum_luse)* (math.log( Sport/sum_luse))
```

ArcGIS Python script used to calculate land use diversity level: formula in field calculator.

```
-1*(Acc(!Accomodation!, !sum_luse! ) + Com(!Commercial!, !sum_luse!) + Edu(
!Education!, !sum_luse!)+ Hea( !Health!, !sum_luse!) + Ind( !Industry!, !
sum_luse!) + Off( !Office!, !sum_luse!) + Oth( !Other_Built_Up!, !
sum_luse!) + Res( !Residential!, !sum_luse!) + Spo( !Sport!, !
sum_luse!))/math.log( !n_luse! )
```

## Calculation of Walkability Indicators

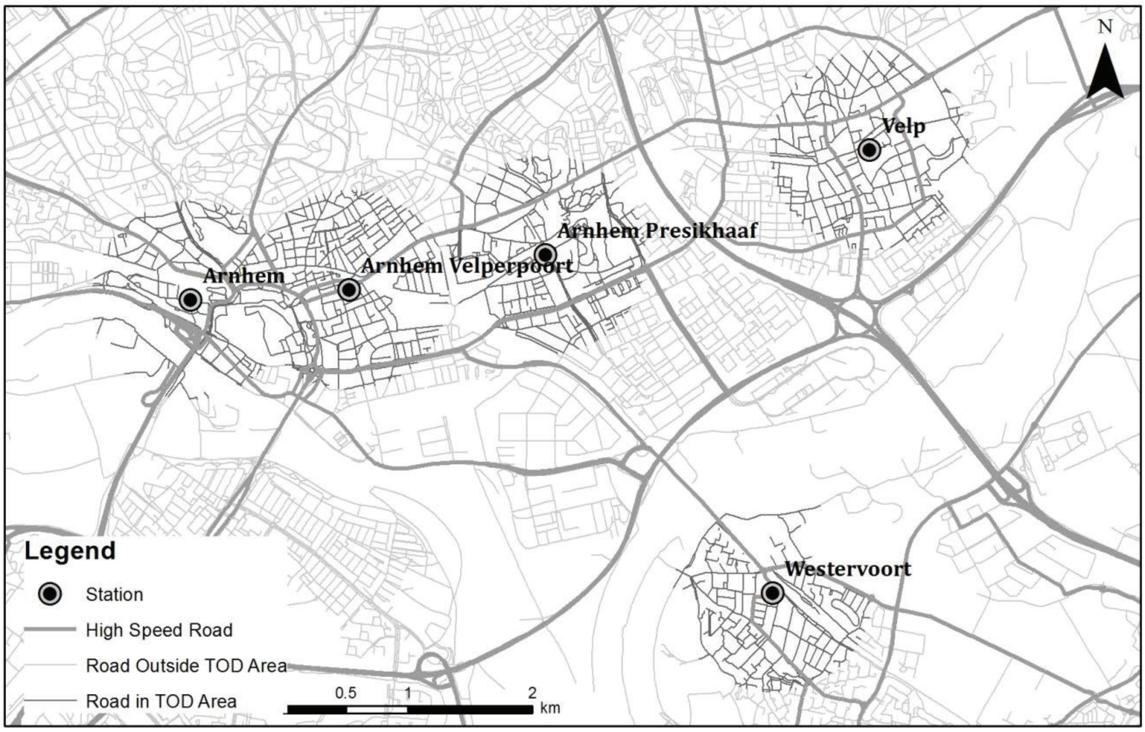
The process of road classification:

| ROAD TopNL (cs_weg) | | |
|---|---|---|
| **TYPEWEG** | **TYPE** | |
| autosnelweg | motorway | |
| hoofdweg | main road | 1736 obj. |
| lokale weg | local road | |
| overig | remaining | |
| regionale weg | regional road | 5407 obj. |
| rolbaan, platform | runway platform | |
| startbaan, landings baan | runway | |
| straat | street | |

| HOOFDVERKEER | HEAD MOVEMENT | classified as | |
|---|---|---|---|
| busverkeer | bus traffic | ---> | overig |
| fietser, bromfietser | cyclists, moped | | overig |
| gemengdverkeer | mixed traffic | | all except autosnelweg |
| overig | remaining | | overig |
| snelverkeer | fast traffic | 1200 obj. | autosnelweg, hoofdweg, regionale weg |
| vliegverkeer | traffic | | rolbaan, platform, startbaan, landings baan |
| voetgangers | pedestrians | | overig |

| | |
|---|---|
| (dark grey) | Removed from Road Layer (1st) |
| (light grey) | Removed from Road Layer (2nd) |

The result of road classification:




## Calculation of Location-Accessibility Indicators

Number of jobs that are accessible within the pedestrian catchment area:

| Station | Number of Jobs | | | |
|---|---|---|---|---|
| | Industrial | Commercial | Non-Commercial | Total |
| Arnhem | 78 | 3669 | 4375 | 8122 |
| Arnhem Presikhaaf | 152 | 454 | 2261 | 2867 |
| Arnhem Velperpoort | 149 | 4086 | 3216 | 7451 |
| Arnhem Zuid | 6 | 302 | 160 | 468 |
| Didam | 343 | 847 | 209 | 1399 |
| Dieren | 363 | 577 | 745 | 1685 |
| Duiven | 2 | 63 | 596 | 661 |
| Elst | 15 | 817 | 346 | 1178 |
| Molenhoek-Mook | 0 | 0 | 0 | 0 |
| Nijmegen | 94 | 1657 | 2826 | 4577 |
| Nijmegen-Lent | 13 | 168 | 368 | 549 |
| Nijmegen Dukenburg | 53 | 9179 | 1251 | 10483 |
| Nijmegen Heyendaal | 75 | 52 | 6504 | 6631 |
| Oosterbeek | 31 | 77 | 302 | 410 |
| Rheden | 0 | 209 | 141 | 350 |
| Velp | 26 | 855 | 346 | 1227 |
| Westervoort | 13 | 636 | 335 | 984 |
| Wijchen | 23 | 4035 | 474 | 4532 |
| Wolfheze | 2 | 18 | 1036 | 1056 |
| Zetten-Andelst | 57 | 375 | 183 | 615 |
| Zevenaar | 280 | 222 | 414 | 916 |

# APPENDIX C: CALCULATION OF PASSENGER LOAD

The table showing the process of calculation of passenger load indicators.

| Station | Passenger (Daily Average): Daily Average | Passenger (Daily Average): Peak Hours (25%) | Passenger (Daily Average): Off-Peak (75%) | Train Operate per hour: ICE P | ICE OffP | Intercity P | Intercity OffP | Intercity (Terminus) P | Intercity (Terminus) OffP | Sprinter P | Sprinter OffP | Sprinter (Terminus) P | Sprinter (Terminus) OffP | Local Train P | Local Train OffP | Operate From | Operate Until | Operation Hour: Hours Of Operation (Total) | Hours Of Operation (Peak Hours) | Hours Of Operation (Off Peak) | Passenger Per Hour: Peak Hours | Passenger Per Hour: Off-Peak | Capacity Per Hour: Peak Hours | Capacity Per Hour: Off-Peak | Passenger Load (Peak Hours) | Passenger Load (Off-Peak) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arnhem | 39374 | 9844 | 29531 | 1 | 1 | 12 | 12 | | | 4 | 4 | 2 | 2 | 6 | 6 | 06.00 | 01.30 | 19.5 | 3.0 | 16.5 | 3281 | 1790 | 3545 | 3545 | 92.57% | 50.49% |
| Arnhem Presikhaaf | 1578 | 395 | 1184 | 0 | 0 | 0 | 0 | | | 4 | 4 | | | 0 | 0 | 06.00 | 01.30 | 19.5 | 3.0 | 16.5 | 132 | 72 | 538 | 538 | 24.46% | 13.34% |
| Arnhem Velperpoort | 3672 | 918 | 2754 | 0 | 0 | 0 | 0 | | | 4 | 4 | | | 12 | 12 | 06.00 | 00.00 | 18.0 | 3.0 | 15.0 | 306 | 184 | 1070 | 1070 | 28.59% | 17.15% |
| Arnhem Zuid | 2109 | 527 | 1582 | 0 | 0 | 4 | 4 | | | 4 | 4 | | | 0 | 0 | 06.00 | 00.00 | 18.0 | 3.0 | 15.0 | 176 | 105 | 1154 | 1154 | 15.22% | 9.13% |
| Didam | 1899 | 475 | 1424 | 0 | 0 | 0 | 0 | | | 0 | 0 | | | 8 | 8 | 06.00 | 00.00 | 18.0 | 3.0 | 15.0 | 158 | 95 | 355 | 355 | 44.55% | 26.73% |
| Dieren | 3936 | 984 | 2952 | 0 | 0 | 4 | 4 | | | 4 | 4 | | | 0 | 0 | 06.00 | 00.30 | 18.5 | 3.0 | 15.5 | 328 | 190 | 1154 | 1154 | 28.41% | 16.50% |
| Duiven | 3865 | 966 | 2899 | 0 | 0 | 0 | 0 | | | 0 | 0 | | | 8 | 8 | 06.00 | 00.00 | 18.0 | 3.0 | 15.0 | 322 | 193 | 355 | 355 | 90.68% | 54.41% |
| Elst | 4843 | 1211 | 3632 | 0 | 0 | 4 | 4 | | | 4 | 4 | | | 4 | 2 | 06.00 | 01.30 | 19.5 | 3.0 | 16.5 | 404 | 220 | 1332 | 1243 | 30.30% | 17.71% |
| Molenhoek-Mook | 1223 | 306 | 917 | 0 | 0 | 0 | 0 | | | 0 | 0 | | | 8 | 4 | 05.30 | 00.00 | 18.5 | 3.0 | 15.5 | 102 | 59 | 355 | 178 | 28.69% | 33.32% |
| Nijmegen | 38651 | 9663 | 28988 | 0 | 0 | 4 | 4 | 4 | 4 | 4 | 4 | | | 4 | 2 | 06.00 | 01.30 | 19.5 | 3.0 | 16.5 | 3221 | 1757 | 2805 | 2689 | 114.84% | 65.34% |
| Nijmegen-Lent | 777 | 194 | 583 | 0 | 0 | 4 | 4 | | | 4 | 4 | | | 0 | 0 | 06.00 | 00.00 | 18.0 | 3.0 | 15.0 | 65 | 39 | 1154 | 1154 | 5.61% | 3.37% |
| Nijmegen Dukenburg | 2477 | 619 | 1858 | 0 | 0 | 0 | 0 | | | 4 | 4 | | | 0 | 0 | 06.00 | 00.30 | 18.5 | 3.0 | 15.5 | 206 | 120 | 538 | 538 | 38.40% | 22.29% |
| Nijmegen Heyendaal | 3287 | 822 | 2465 | 0 | 0 | 0 | 0 | | | 0 | 0 | | | 8 | 4 | 05.30 | 00.00 | 18.5 | 3.0 | 15.5 | 274 | 159 | 355 | 178 | 77.12% | 89.55% |
| Oosterbeek | 482 | 121 | 362 | 0 | 0 | 0 | 0 | | | 4 | 2 | | | 0 | 0 | 05.30 | 00.30 | 19.0 | 3.0 | 16.0 | 40 | 23 | 538 | 269 | 7.47% | 8.41% |
| Rheden | 993 | 248 | 745 | 0 | 0 | 0 | 0 | | | 4 | 4 | | | 0 | 0 | 06.00 | 00.30 | 18.5 | 3.0 | 15.5 | 83 | 48 | 538 | 538 | 15.39% | 8.94% |
| Velp | 1433 | 358 | 1075 | 0 | 0 | 0 | 0 | | | 4 | 4 | | | 0 | 0 | 06.00 | 00.30 | 18.5 | 3.0 | 15.5 | 119 | 69 | 538 | 538 | 22.21% | 12.90% |
| Westervoort | 500 | 125 | 375 | 0 | 0 | 0 | 0 | | | 0 | 0 | | | 8 | 8 | 06.00 | 00.00 | 18.0 | 3.0 | 15.0 | 42 | 25 | 355 | 355 | 11.73% | 7.04% |
| Wijchen | 3764 | 941 | 2823 | 0 | 0 | 0 | 0 | | | 4 | 4 | | | 0 | 0 | 06.00 | 00.30 | 18.5 | 3.0 | 15.5 | 314 | 182 | 538 | 538 | 58.35% | 33.88% |
| Wolfheze | 760 | 190 | 570 | 0 | 0 | 0 | 0 | | | 4 | 2 | | | 0 | 0 | 05.30 | 00.30 | 19.0 | 3.0 | 16.0 | 63 | 36 | 538 | 269 | 11.78% | 13.25% |
| Zetten-Andelst | 732 | 183 | 549 | 0 | 0 | 0 | 0 | | | 0 | 0 | | | 4 | 2 | 06.30 | 23.30 | 17.0 | 3.0 | 14.0 | 61 | 39 | 178 | 89 | 34.35% | 44.16% |
| Zevenaar | 4652 | 1163 | 3489 | 0 | 0 | 0 | 0 | | | 0 | 0 | | | 8 | 8 | 06.00 | 00.00 | 18.0 | 3.0 | 15.0 | 388 | 233 | 355 | 355 | 109.14% | 65.48% |

Peak Hours : 07.00-08.30
16.30-18.00

(shaded) Terminus

The capacity of station Non Terminus
are assumed as occupied 40% in each station

# APPENDIX D: SENSITIVITY ANALYSIS

The weight used to perform the sensitivity analysis.

| | Criteria | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Passenger Load | User Friendly | Access | Parking | Density | Diversity | Pedestrian | Economic |
| 0 Base Weights | 0.1944 | 0.1111 | 0.1528 | 0.0833 | 0.1528 | 0.0278 | 0.0556 | 0.2222 |
| 1 Passenger Load +10% | 0.2139 | 0.1083 | 0.1500 | 0.0806 | 0.1500 | 0.0250 | 0.0528 | 0.2194 |
| 2 Passenger Load -10% | 0.1750 | 0.1139 | 0.1556 | 0.0861 | 0.1556 | 0.0306 | 0.0583 | 0.2250 |
| 3 User Friendly +10% | 0.1929 | 0.1222 | 0.1512 | 0.0817 | 0.1512 | 0.0262 | 0.0540 | 0.2206 |
| 4 User Friendly -10% | 0.1960 | 0.1000 | 0.1544 | 0.0849 | 0.1544 | 0.0294 | 0.0571 | 0.2238 |
| 5 Access +10% | 0.1923 | 0.1089 | 0.1681 | 0.0812 | 0.1506 | 0.0256 | 0.0534 | 0.2200 |
| 6 Access -10% | 0.1966 | 0.1133 | 0.1375 | 0.0855 | 0.1550 | 0.0300 | 0.0577 | 0.2244 |
| 7 Parking +10% | 0.1933 | 0.1099 | 0.1516 | 0.0917 | 0.1516 | 0.0266 | 0.0544 | 0.2210 |
| 8 Parking -10% | 0.1956 | 0.1123 | 0.1540 | 0.0750 | 0.1540 | 0.0290 | 0.0567 | 0.2234 |
| 9 Density +10% | 0.1923 | 0.1089 | 0.1506 | 0.0812 | 0.1681 | 0.0256 | 0.0534 | 0.2200 |
| 10 Density -10% | 0.1966 | 0.1133 | 0.1550 | 0.0855 | 0.1375 | 0.0300 | 0.0577 | 0.2244 |
| 11 Diversity +10% | 0.1940 | 0.1107 | 0.1524 | 0.0829 | 0.1524 | 0.0306 | 0.0552 | 0.2218 |
| 12 Diversity -10% | 0.1948 | 0.1115 | 0.1532 | 0.0837 | 0.1532 | 0.0250 | 0.0560 | 0.2226 |
| 13 Pedestrian +10% | 0.1937 | 0.1103 | 0.1520 | 0.0825 | 0.1520 | 0.0270 | 0.0611 | 0.2214 |
| 14 Pedestrian -10% | 0.1952 | 0.1119 | 0.1536 | 0.0841 | 0.1536 | 0.0286 | 0.0500 | 0.2230 |
| 15 Economic +10% | 0.1913 | 0.1079 | 0.1496 | 0.0802 | 0.1496 | 0.0246 | 0.0524 | 0.2444 |
| 16 Economic -10% | 0.1976 | 0.1143 | 0.1560 | 0.0865 | 0.1560 | 0.0310 | 0.0587 | 0.2000 |