Developing a walkability index for the assessment of nodes in a Transit-Oriented Development

Case Study in Nijmegen, the Netherlands

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March 2017

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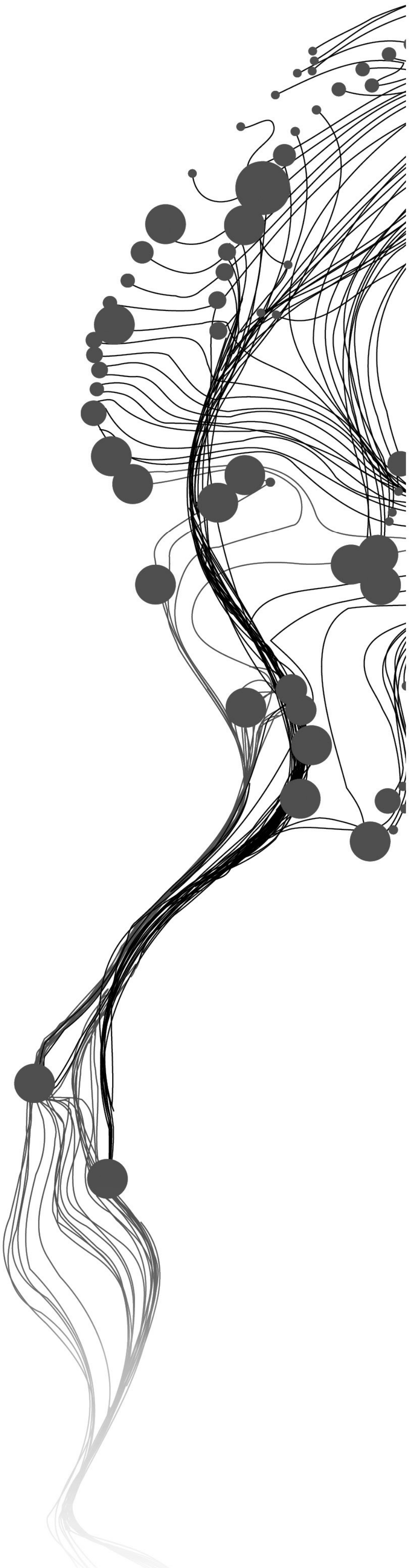

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

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ABSTRACT

Transit-Oriented Development (TOD) is an approach that is well researched and established for aiding policy makers and planners in dealing with the problems derived from urbanization, increased transit needs and managing land-uses and land values. Typically, the TOD approach focuses on integrating mixed land uses, high-quality living and working environments, and opportunities that encourage mass public transport and using non-motorized means of transit such as cycling and walking. To measure a TOD's ability to encourage these aspects, researchers have often focused on the so-called 3Ds: Density, Diversity and Design, linked with urban form, which were later extended to include Distance to transit and Destination accessibility. However, the focus of these assessments tends to be on the dimensions of Density and Diversity that better capture the relationships between land-uses, land-values and opportunities for densifying a transit node/ station.

The design dimension is often reduced to calculating infrastructure-related indicators linked with non-motorized forms of transport, i.e. length of bicycle/ pedestrian networks, and intersection density. This is a very simple way to measure the opportunities of a built environment to promote/ enhance walkability and pedestrian movements, as it is shown by an extensive body of research from the urban design field. Moreover, when pedestrian infrastructure around transit nodes is adequate, the so-called TOD-ness of the area will increase because transit will be more accessible.

Bringing together these two fields, this paper develops a walkability index that can further enhance the assessment of the Design dimension, and the inclusion of walkability concerns in the development and assessment of a TOD environment. The indicators were developed according to three main dimensions: Accessibility, Safety, and Urban Design, and applied to two stations in the city of Nijmegen, in the Netherlands. A buffer of 400 meters radius that represents 5-minutes walking distance was considered around each node for data collection and analysis. The indicators were analyzed by referring to secondary data of street network, and using impact levels to define threshold and assign scores. A base model was applied for the case study and to obtain the score of the full index. The indicators were also visualized through ArcGIS to help the understanding of the walkability assessment. Results indicate that the area in the vicinity of the stations tend to invite walkability, any weak performance in the walkability index is partly due to the criteria of 'attractiveness' in this study. This criteria relates to the 'urban design'.

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1 Introduction

This chapter offers an introduction in terms of background and justification, following up the research gap and then the research aims and objectives. The chapter ends up with the description of the thesis structure.

1.1 Background and justification

Rapid urbanization is in progress and has led to extensive land use change influencing the development of many cities. Severe problems such as the excessive use of cars with the change of the land use patterns, influence how people travel in a community. The percentage of population living in urban areas shows a current explosive growth reaching around 80% in most European countries (Antrop, 2004). Many of the initial advantages that attracted people to settle in suburban areas are lost because of the increased densification of the urban fabric and related congestion problems (Antrop, 2000). Given the urbanization trends, land use factors such as density, regional accessibility, mixed uses level and walkability have been studied to understand what is useful for evaluating the ability of the urban revival of '*smart growth*', which includes development of sustainable transportation system and more efficient uses of land in close proximity (Pollard, 2001). The urban design movement called '*New Urbanism*', which promotes the environmental friendly habits also has a goal of 'finding ways to manage sprawl and improve our total quality of life'(Staley, 2004).

Among those concerns that arose from the densification of urban areas, worsening traffic congestion is expected to remain a challenge especially in urban areas. Sustainable approaches to reduce these problems while ensuring the continuous growth of the city are most pressing. Transit-Oriented Development (TOD) is an approach of promoting *smart growth* to urban and transport planning that has been used by many fast-growing cities to alleviate their congestion problems. The typical definition of TOD concept is based on the integration of mixed land use and transport system, to create lively spaces and neighborhoods that potentially increase biking and walking and public transport uses (Cervero et al., 2004).

TOD's focus of locating new construction and redevelopment in and around transit nodes is viewed by many as a promising tool for curbing sprawl and the automobile dependence it spawns (Cervero et al., 2004). However, it is worth noting that there is no authoritative interpretation of TOD. Many researchers have studied the general term of TOD while overlooking other key factors affecting the use of transit. An example is the case of the most ambitious rail expansion in Dallas, which in the name of the TOD approach turned out a failure that lead to increased emissions, climate change, congestion and less reliable surface transit (Baum-Snow & Kahn, 2000). The main reason for this outcome was the lack of investment in regional infrastructure to make the transit more attractive. Factors such as the insufficient residential densities, excessive downtown parking, infrequent service and a lack of walkable environments are also elements that fail to support the orientation towards and facilitation of transit (Speck, 2014).

By far there are very few examples where TOD results were quantified to confirm the performance of TOD project. Some urban indicators have been measured separately but a comprehensive TOD measurement combining a crucial evaluation of urban design features is lacking. With the idea of '*New Urbanism'* and its human-scaled design which calls for a return to compact neighborhoods with grid-like street patterns, mixed land uses and pedestrian amenities (Cervero & Radisch, 1996a), a walkable neighborhood and its walkability is being identified as a key feature of a TOD, which is clearly associated with a walkable environment (Jacobson & Forsyth, 2008).

Concepts of urban design have been put forward in literature by showing a more integrated evaluation of TOD. The "Design" variable is well known by an analytical approach that has been discussed and explored by the formidable duo Cervero and Kockelman (1997) in their travel demand studies. Some proponents believe that travel mode shift causing reduced area-wide traffic congestion and improved air quality will be induced by a combination of "design features" (Niles & Nelson, 1999). Among several case studies of the world's major cities aimed "transit-oriented urban design", Fang (2011) brings up the guidelines of pedestrian-oriented design which involves the promotion of walkable and safe environment, interesting and lively adjacent land uses, climatic conditions etc. There, walkability is increasingly valued not only because of the reduction of traffic congestion and environmental impact, but also because it is embedded in urban design concept that ranges from health issues to the social and recreational value of spaces designed to promote walking. These are affected by the attraction of footpaths, the presence of sidewalks among other pedestrian facilities, traffic and road conditions, as well as land use patterns. Walkability is thus essential to TOD theory as it describes the transit corridors that can be improved in order to simultaneously enhance both the transit and the urban fabric (Speck, 2014).

1.2 Research gap

It is sometimes forgotten that the best solution comes from amending the basics, that is, the walkability can be the key component to a TOD approach wherein the pedestrian access refers to the built environment between the transit stop and the immediately surrounding area. In existing TOD research, Singh (2015) developed a TOD index where one of the criteria regarding the design dimension is a combination of bikeability and walkability. Even though the two are related when it comes to the TOD environment, the bikeability dimension is out of the scope of this research, however being studied by another ITC MSc researcher, also in 2017 (Mr. Kurniawan Hartanto). The larger issues of the integration of land use and transportation, of which the focus is on the density or land use dimensions relevant to the overall understanding of smart growth and TODs, are also not the main concern of this thesis. This particular research claims that the opportunities for pedestrian movement should be highlighted in understanding and evaluating TOD projects (Schlossberg & Brown, 2004), thereby walkability indicators are the primary focus of this thesis, especially the design features of the walking environment.

1.3 Research aim and objectives

This thesis builds up on the recognition that most TOD projects overlook the potential of urban design that could significantly influence the performance of a TOD node. Hence, the general objective of this research is: *to develop an index that measures walkability indicators to enable the assessment of TOD nodes in order to enhance the physical environment of transit corridors. The Nijmegen city in the Netherlands will be used as a case study.* In this research, indicators related to walkability around TOD nodes will be selected from relevant literature and supported by fieldwork. These indicators will be used to calculate a walkability index. Some of the indicators will use the measurement of **level of impact** by giving descriptions from high level to the low, and accordingly each street segment will have a different score. A percentage-based method is also used to measure the indicators. Two railway stations will be chosen to see differences that will help in evaluating the index's performance. More detailed methodology is presented in Chapter 3.

The main objective of the thesis will be addressed by focusing on the following research questions:

1. To review methods in literature that measure walkability in a TOD environment.

- Why is walkability important in a TOD environment?
- How has the design element for walkability been included in TOD research so far?
- What are the indicators that can be used for building the walkability index around transit nodes?
- What are the main measurements of walkability that can be found in literature?

2. To design a walkability index that is appropriate in a TOD context.

- How to define the immediate surrounding areas of the transit nodes?
- How will the indicators be measured in an index?

3. To demonstrate the applicability of the walkability index in a case study.

- How can the refined indicators be introduced in the local context?
- How to visualize the walkability indicators in GIS and walkability indexes between stations?

4. To analyze differences in walkability index values in a case study.

- What are the differences and similarities between the nodes in terms of walkability index?
- What is the main findings and further steps according to the results?

1.4 Thesis structure

This thesis is structured in the following way. After this introduction, Chapter 2 describes the main measurements that have been used to produce the criteria and indicators of walkability in literature, as well as the exploration of the walkability concepts and the research's emphasis of the design dimension in a TOD context. Chapter 3 presents and elaborates on the methods used for data collection and analysis, and how the index is developed. The results of the application to the two station areas in Nijmegen are presented in Chapter 4, with the visualization of each indicator and interpretation of the results with comparable tables. In the conclusion part of Chapter 4, the variation of the index and the relative importance of each aspect to the walkability are observed by using numbers and charts. The final chapter discusses main findings of this thesis including contribution, limitation and further development from this study.

2 Literature Review

This chapter presents the review of the relevant literature, guided by the research questions of why is walkability important in a TOD environment, how has the design element for walkability been included in TOD research, and what are the indicators that can be used for building the walkability index around transit nodes. In the last section of this chapter the main measurements of walkability in literature are explored.

2.1 Transit Oriented Development

Transit-oriented Development (TOD) is a modern planning strategy, first developed by Peter Calthorpe and presented in his "The New American Metropolis", in 1993. Cervero (1996) then conducted a comparative analysis between auto-oriented city and transit-oriented city and proved that there is 30% less travel volume by cars. The typical definition of TOD concept in history is formed and based on the integration of mixed land use and transport system, thereby creating lively spaces and neighborhoods that potentially increase biking, walking and use of public transport (Cervero, 2007). From then on, the concept of TOD has been disseminated across United States and other western countries not only in theory but also in practice, mainly because its characteristics of mixed use and higher density can play a role in increasing physical activity (Thrun, Leider, & Chriqui, 2016).

In order to achieve sustainability in the context of urban planning, transit-oriented development is often discussed with other influential planning movement i.e. the *new urbanism* and *neo-traditional planning* because of their benefits of calming the traffic and related pollution (Crane, 1996). These movements have a similar goal of finding solutions to manage urban sprawl under the urbanization trends and improve the quality of life. Land use factors in TOD concept such as density, regional accessibility, mix level and walkability contributes to the opportunities concerning land value that are derived from co-location of transit and employment or residence centers (Newman & Kenworthy, 1996). Until so far, Speck (2014) has argued in his New Mexico analysis that the traditional wisdom creating a strong economy followed by a higher quality of life needs to be replaced by the converse that creating a higher quality of life is the first step towards attracting young and smart people with their new jobs and residents.

2.2 Walkability Research

2.2.1 Origin from health promotion

For years, walkability has received attention from multidisciplinary fields for its benefits related to public health. The societal problems caused by urbanization, coupled with the environmental degradation, are seeking a turn from unhealthy lifestyles of using less human-powered modes of transport like walking and cycling, to sustainability (Saelens, Sallis, & Frank, 2003a). Many researches have noticed that there has been an increase in obesity among their citizens (Casagrande, Gittelsohn, Zonderman, Evans, & Gary-Webb, 2011). Although connected to basic transportation but also relevant to other anthropological issues at the same time, the walkability tends to be the cross-sectional research nowadays. But it was in fact initiated by preventive medicine field that promoted good health through walking (Saelens, Sallis, & Frank, 2003b). In the scope of the walkability research that aims to promote physical activity and the promotion of public health, the question of how the built environment can influence modal shift from private automobile to walking has become a main debate (Fuller, Gauvin, Kestens, Morency, & Drouin, 2013). This is important because the interventions focus on public activities, the physical movements for which, tend to be moderate-intensity type rather than vigorous type (Pikora, Giles-Corti, Bull, Jamrozik, & Donovan, 2003).

Previous research has tried to capture subjectivity and people's perception of the built environment, but this is challenging and has several limitations (Michael, Beard, Choi, Farquhar, & Carlson, 2006). This is partly because unlike the physical activity for health/ sport reasons, walking behavior can happen under various circumstances for various kinds of purpose (Pikora et al., 2003). Because it is difficult to measure the psychological and social factors that influence the individual's perception, functional factors such as street-level design, have been dominating most walkability research especially in transportation planning process (Park, 2008).

2.2.2 Walkability in transport-related research

On the side of traffic management, apart from the provision of the routes for walking, motivations have been generated to improve walking environments and encourage non-motorized transportation modes (Schlossberg & Brown, 2004). The field of transportation planning has developed close findings to public health towards the correlation between neighborhood characteristics and walking for transportation (Pikora et al., 2003), by for example stimulating physical activity and decreasing auto emission pollution. However, the 'built environment' on the transportation side tends to examine the broader scale in relation to higher residential density, mixed land uses and connected street patterns, which have been proved to be correlated to higher walking rates at neighborhood scale. These three variables indicate the accessibility dimension, more specifically on the basis of considering distance and directness of travel. Walkability as a function in traffic-related field includes the two largely used aspects of **proximity** and **connectivity**. In other words, the increased residential density and land use diversity mean shorter distance to the public transit, and the grid-like street which is compact and connected means short size of block lengths and fewer barriers that improve the level of ease and connectivity between the origin and destination.

Earlier studies on walkability from the transportation field have proven the positive correlation between the mixed land use and physical activity like walking (Cervero, 1996; Hess, Moudon, Snyder, & Stanilov, 1999; L. D. Frank, 2000). Urban sprawling and freeways have led to low-density development leading to auto dependency. This type of development has generated several problems, like increased obesity rates, an expansion over surrounding suburban areas, and unequal levels of accessibility, with the population segment that cannot drive being overly dependent on others for their mobility. These are amongst the arguments in favor of "neo-traditional" development in studies on higher housing density, as well the mixed land use, especially around public transit (Brenner, 1999; Black, 1996). The grid-like street patterns as a sign of compact neighborhood has also been involved in the new urbanism movements, coupled with other pedestrian-oriented development proved to have the apparent effect on work trips, and foster the travel trips by walking (Cervero & Radisch, 1996b).

2.3 Walkability in the context of Transit-Oriented Development

2.3.1 Walkability in TOD planning

Walkability is important in a TOD context because non-motorized forms of transit feed transit stations, provide low-budget alternatives to the private automobile, reduce congestion, and increase livability in the neighborhoods. Therefore walkability is a key cornerstone of a successful TOD project, where inhabitants are discouraged from using private transport and instead take non-motorized forms of transport and public transit for their daily travel. The TOD's pursuit of a combination of transit and walking environment is demonstrated through the literature on empirical studies where the 3Ds of TOD "Density, Diversity and Design" were identified by (Cervero & Kockelman, 1997) further elaborated in to the 5Ds of the built environment as "Density, land use Diversity, pedestrian oriented Design, Destination accessibility and Distance to transit"

(Ewing & Cervero, 2001). Among these studies, which are aiming to reduce car dependency and encourage more public transport, the importance of walkability in a TOD context can be recognized as the contribution of achieving TOD objectives through establishing a pedestrian friendly environment.

2.3.2 Link of walkability and urban design

A key goal of transit-oriented development has been identified towards the design dimension and its role in creating a walkable environment. Literature suggests that the walkability in TOD context is explained as the transit-oriented design, in which the growing demand for walkable and transit-oriented development has been the concern. Urban design aspects include street, footpath, park and other aesthetic aspects (Ewing, 2000). The specialty of walking environment in TOD context is that "since all transit trips involve some degree of walking, it follows that transit-friendly environments must also be pedestrian-friendly" (Cervero & Kockelman, 1997, p. 91).

Plenty of urban design studies do not provide clear distinction between urban design and urban planning. This is due to the evolution in urban planning's history that many more socio-economic aspects have been covered now than before, leading to a mixed-up interpretation of urban design and urban planning. Schurch (1999) tries to give urban design a practical definition, as "being form-giving to built environments as primary activity involving the professions of architecture, landscape architecture and planning". In this study of urban design towards walkability, even though some features of urban design are shared with urban planning, the scale of intervention for the urban design is, in this case, opposed to the larger scale, where the visions and master plans planned under urban planning field (Madanipour, 2006). In fact, urban design has been out of the mainstream planning process for years, and it began to regain itself as a profession only recently because of the sustainable needs of pedestrian as neo-traditional and lasting trend of development in now and coming era.

2.3.3 Walkability in the European TOD context

Another reason to address the dimension of design is based on the TOD context in some European cities, for example, the Dutch context where the case study will take place. In the Netherlands most cities have a mature system of transportation and planning. Pojani & Stead (2015) implied the rediscovery of TOD in Europe that the "new TOD projects are often seen as important contributors to good urban design to coordinate transportation modes, mix land uses, and create an appealing public space within a limited area", They argued that in this contemporary trend on urban design in Europe, TOD is more focused on aesthetics, with its form of getting new opportunity and global attention by responding to the recent economic crisis. In history, earlier ideas of train-based urban development are the foundation of TOD that originated and developed in most of European cities around 19th and 20th centuries (Newman & Kenworthy, 1996). Until now, factors of TOD such as density and mixed land use have remained unchanged, except for the new potential investment on aesthetics (Schrenk et al., 2016).

With the existing immature solutions against mature system of planning in Europe, the design aspects such as architecture and greenery are needed to be discussed as they promote walking or create 'pedestrian-friendly environments' more than in theories and discourses. However, the related research is often based on little evidence and these factors have been shown to be insignificant in the quantitative analyses on the amount of walking. Additionally, the main discussion of walkability in the TOD context often leads to solely transportation planning whilst overlooking the design aspects that contribute to walkability in a TOD context.

2.4 Measuring walkability

2.4.1 Walkability Index

In order to understand and measure walkability, it is suggested by Lo (2009) to identify the points of agreement and disagreements between "metrics" for walkability. Those metrics, in other words, are several tangible and concrete walkability components divided by a measuring tool named a walkability index.

These components, however, are not discrete and often shape the walkability with a combination in a form of composite walkability index. Cervero & Kockelman (1997) discovered that the "spatial multicollinearity" exists when it comes to the relationships between the built environment and pedestrian access, meaning that these two aspects should be seen as complementary that influence each other. A composite walkability index can offer an overall value of walkability to measure the physical environment but also show the relative performance of the walkability indicators used (Lawrence D. Frank, Schmid, Sallis, Chapman, & Saelens, 2005). An integrated walkability index is developed and presented in the next chapter, on the basis of an extensive literature review.

There is no one-fit-for-all measurement in walkability, and the selected indicators for walkability are diverse due to their different purpose in existing literature (Handy, 1996). In previous TOD research, the indicators selected were the most direct and quantifiable to compose a TOD index (Y. J. Singh, Zuidgeest, Flacke, & van Maarseveen, 2012). However, walkability measures vary by needs of pedestrians, for example their specific trip purpose or other determinants such as their socio-economic characteristics (Manaugh & El-Geneidy, 2011). A study in Australia showed that there was a strong positive association between walking for transport and physical environment attributes, whilst there is little significant correlation between environmental factors and walking for recreation (Owen et al., 2007). Thus, the hypothetical idea in this thesis is that the physical environment that matches the pedestrians' needs will have more people walking in it, and hence also contribute to building a successful TOD.

2.4.2 Measuring walkability in existing research

1. There have been methods developed to address the challenge of measuring and analyzing different scales/ levels in walkability research (Moayedi et al., 2013). A walkability plan in Kansas City was adopted by its City Council in 2003, where the need to integrate different scales of analysis is taken into account (Dannenberg, Cramer, & Gibson, 2005).This is due to the recognition of the fact that one size does not fit all and each area type requires different standards and techniques. Therefore, in this example, the authors measured walkability in a pedestrian environment at a citywide and neighborhood and district levels separately. The authors also pointed out that the methods vary depending on if the project is run by a public organization or by a private entity. There are four categories of methods that range from the macro city scale down to the project specific scale in the Kansas example, and it provides a representative overview of possible existing methods for measuring walkability at different levels (figure 2.1).

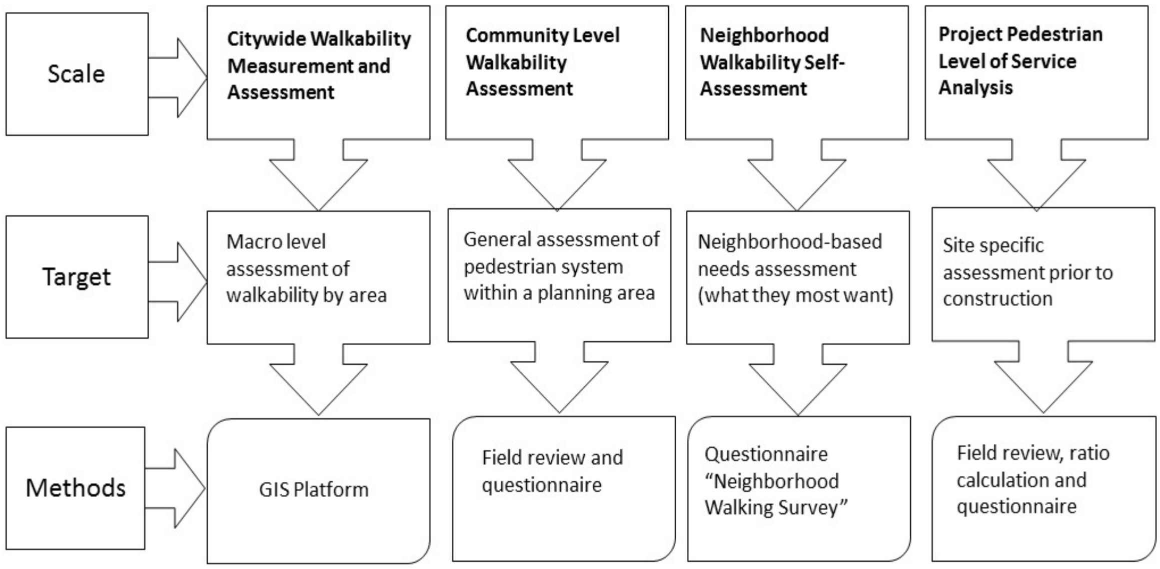


Figure 2-1: Methods of measuring walkability

The walkability indicators in the Kansas City case include the same contents at each level but some of them have different descriptions and measurements. The indicators are directness, continuity, street crossing, physical interest and amenities, and security. By building a form of walkability index at a smaller scale, the useful indicators with their descriptions are classified into two dimensions out of four which are summarized in table 2-1. A walking survey at the neighborhood level was conducted using mapping exercises, by handing-out maps to their respondents. And for the project pedestrian level, the measurement of facility-specific level-of-service resulted in six groups ranging from A to F, where the performance of A is excellent and F is worst.

Table 2-1: Walkability in Kansas (USA)

Dimension	Indicators	Description
Neighborhood (day-to-day needs and desires of the community)	Directness	Directness to where you want to walk to
	Continuity	Completeness of pedestrian sidewalk system to get there
	Street Crossing	Major arterials that are difficult to cross
	Physical Interest and Amenities	Pedestrian scale, friendly
	Security	Visual line of sight and street lighting
Project	Directness	Actual walk time compared to minimum walk time characterized by a grid
	Continuity	Completeness of pedestrian system and integration with project and surrounding uses
	Street Crossing	Number of lanes to cross plus pedestrian crossing features
	Visual Interest and Amenities	Presence of landscape/hardscape, parkways, medians, street lights
	Security	Visual line of sight and street lighting

This Kansas case gives an overview of how to measure the walkability under different scale levels according to specific needs and provides a comprehensive overview of potential indicators to be used in the assessment of walkability, together with how to measure the indicators.

2. A study in Greece developed an audit tool with two checklists of street segments and crosswalks to compare the urban roads especially in European cities. This walkability measurement was applied to a Greek example and examined separate street segments and crosswalks (Athanasios & Nikolaos, 2010). This self-observation audit tool allows observation directly and systematically. It represents the characteristics of the urban environment and helps in comparison of different sites. The authors argued that the usefulness of the tool resides in the fact that it meets both the research needs and the decision making process within a community as it is a useful information management tool that make clear the contribution made by information and services through identification, costing and rationalization. The checklists were improved by including as many aspects of environmental characteristics as possible (e.g. the path slope and pavement surface) to have a comprehensive view of pedestrian problems and thus their potential solutions. However, the audit tool does not emphasized enough on the correlation among items and thus may cause difficulty in identifying specific problems. Also, it should not be a replacement of list of indicators

since there is duplication and repetition in describing walkability aspects. But otherwise it is helpful to extensively develop a set of walkability indicators by choosing from the checklists (table 2-2).

Table 2-2: Walkability in a Greek case

Dimension	Indicators
Road segment	Land use
	Pedestrian infrastructure
	Path location
	Path slope
	Grade
	Pavement surface
	Path condition & smoothness
	Sidewalk continuous
	Obstacles in pedestrian route
	Street furniture
	Vehicles parking in the sidewalk
	Weather protection
	Street lighting
	Street cleanliness
	Road users
	Pedestrians walking behavior
Crosswalk checklist	Type of crossing
	Crossing control
	Crosswalk material
	Crosswalk conditions & smoothness
	Crosswalk surface alignment
	Sidewalk-crosswalk connection
	Ramp convenience
	Corner obstacles
	Lighting
	Pedestrian crossing behavior

3. Another representative study of measuring walkability in a transit setting was applied in the case of Lisbon, where seven walkability dimensions, the seven Cs (connectivity, convenience, comfort, conviviality, conspicuous, coexistence and commitment) were developed by Cambra (2012). The author addressed various scales in his walkability assessment that identifies the Mesoscale as the walkable service area from a certain point and the Microscale as design features at a street level. In his research, two levels of **specification** were used by referring to a methodological approach for the improvement of visual attractiveness as its main concern (Batista e Silva, da Graça Saraiva, Loupa Ramos, & Bernardo, 2013). This approach developed several *fundamental viewpoints*

defined as the overall factors that assess the built environment, accordingly with *elementary viewpoints* that can be measured and operationalized. From this point of view, a similar structure of walkability indicators has been drawn from the **specification** as a reference in Cambra (2012)'s study. Table 2-3 developed a group of indicators on the basis of Cambra's Cs that shows the concerns of design factors in walkability.

Table 2-3: Walkability in a case in Lisbon (Portugal)

Dimension	Indicators	Description
Connectivity	Pedestrian network continuity	The extent to which a pedestrian can follow a path using a proper infrastructure that includes sidewalks and crossings.
Convenience	Sidewalk available (net) width	By means of regulations it is possible to establish a minimum sidewalk width to allow the passing of wheelchairs and baby carts and to accommodate the expected pedestrian volume.
Comfort	Amenities	"Increase in its attractiveness or value or that contributes to pedestrian's comfort or convenience"
	Trees	From climate protection (shade and rain cover) to aesthetic composition, to being a link to the natural environment.
	Climate protection	Climate is not regarded as a built environment factor. However it is possible to assess the built environment's response to climate, like provision of protection and shelter from rain and sun etc.
	Lighting	The existence of street lighting is a factor that affects the pedestrian comfort, by allowing to see and to be seen, which may reinforce the perception of safety.
Conviviality	Blind or walled path	The absence of relations between the interior of buildings and their exterior may contribute to the perception of an unsafe environment. Street paths composed of mainly blind or walled paths tend to be used less and therefore less convivial.
	Building frontage transparency	The relationship between the interiors of the buildings and the streets from the outside contribute to the perception of a safe walking environment.
Conspicuous	Path enclosure	Enclosure can be understood as the ability of the outdoor space in creating "walls" (by means of buildings or trees. for instance), with these "walls" contributing to a more clear understanding of the path by the pedestrian.
Coexistence	Conflicts	This fundamental viewpoint refers to the ability of the pedestrian space to coexist with other transport modes (motorized or not).

	Sidewalk buffer width	The buffer zone functions as a segregation enforcer, keeping both pedestrians and vehicles from interfering with each other's space.
Commitment	Maintenance	A proper and well-kept sidewalk, apart from being a comfortable or as a convenient sidewalk, is primarily a more attractive sidewalk than a poor-kept sidewalk.
	Cleanliness	A clean sidewalk apart from being a comfortable or a convenient sidewalk is a more attractive sidewalk than a dirty sidewalk.

Cambra's measurement for his components of walkability used the measurement of impact levels at different scales as well. It is more a function of design, in which a system of pedestrian improvements provides citizens an opportunity to walk. Cambra gave the detailed descriptors for each of the components and their recommended standards and levels that can be learned from, offering a method in the consideration of how neighborhoods can conduct their own self-evaluation of their pedestrian system.

4. An American study, in Portland city Schlossberg and Brown (2004) emphasize the walking accessibility to better understand how the form of the street network can give insight into "how well TOD designs are consistent with walkability". The primarily focus of Schlossberg's study is the connectivity of the pedestrian access towards the theoretical TOD zone of a quarter mile or a half mile. The measurements for the walkability indicators include the classic analysis of PCA (a percentage between the Euclidean distance and the network distance from a station) and intersection density in the transport field, of which the functional characteristics have been treated as the very fundamental elements to measure **connectivity** in walkability research (Leslie et al., 2005). Schlossberg (2004) takes into account the impedance of high volume and high speed roads and dead ends to assess the **continuity** of the network as part of the walkability indicators (table 2-4). This research didn't take into account urban design of streetscape that affects how pedestrian-friendly the environment is. Additionally, he assumed all roads have sidewalks and all the classified roads share the similar characteristics, something that can was further refined in this thesis.

Table 2-4: Walkability in a case in Portland (USA)

Dimension	Indicators	Description
Accessibility/ Connectivity (walking accessibility)	Quantity of Accessible Paths	All the streets in a section are considered equal type and are shown in white by lines of the same thickness.
	Quantity of Impedance Paths	The same neighborhood but with the major auto-oriented streets removed from the walking routes.
	PCA	The data is presented as a percentage between the Euclidean distance and the network distance from a transit station.
	IPCA	A re-calculated PCA, but with the high speed and high volume roads removed.
	Impedance-based Intersection Intensities	The concentration of intersections, which is indicative of pedestrian choice (three and four way), and the concentration of dead-ends

5. Based on Schlossberg's PCA and his consideration of impedance, a similar method of MPCA in a Italian study aims to contribute to sustainable mobility system and treat the pedestrian network as a key factor (Gori et al., 2014). In this study the calculation was made without the major roads or "pedestrian hostile roads" (Gori et al., 2014). The difference is that the MPCA reduces the travel distance by considering the possible delays, instead of directly removing those unfriendly roads to pedestrians as done in Schlossberg's study (2004). There are some issues that could be raised in this Italian case, like that there may be an overlap between PCA and MPCA because in most cases the MPCA values differ from the PCA's by less than 10%. However, the study still considers the MPCA as it has smaller bias in judgment based on relative terms such as a good and a bad walking environment. An example for this is the presence of main road crossings where cycle time of green light for vehicles is longer than for pedestrians (Gori et al., 2014).

Another contribution of this study is the provision of a benchmark for the quantitative analysis, by using two representative TOD locations in Lucca and Venice, in Italy. Additionally the results address the importance of comparing references values from a study in the American context with data from studies in the European context, which can give some insights for this present study. The useful walkability indicators drawn from the Italian study are collected in the table 2-5, most of which count the total or calculate an average within the theoretical area.

Table 2-5: Walkability in a case in Italy

Dimension	Indicators	Description
Proximity	PCA (%)	The percentage of the buffer area of the pedestrian network over a Euclidean buffer area within the maximum acceptable walking distance.
	MPCA	Taking into account the delay that occurs for crossing signalized intersections, and the IA (area defined by Euclidean distances with its unit is m^2).
Connectivity	Nodes number	Number of nodes inside IA
	Nodes density(m/ha)	Average number of nodes per hectare inside IA.
	Links number	Number of road links inside IA
	Links density	Average length of road links per hectare
	Links length(m)	Total length of road links inside IA
	Blocks number	Number of blocks inside IA
	Blocks density(ha/block)	Average dimension of each block
	Links number (Type 2)	Number of road links of Type 2 (two or more lanes in each direction and high traffic volume or high average speed) inside IA.
	Links number (Type 1)	Number of road links of Type 1 (fewer than two lanes in each direction and low traffic volumes or low average speed) inside IA.
Quality	Links of Type 2 (%)	Value of road links of Type 2 compared with number of road links inside IA
	Links of Type 1 (%)	Value of road links of Type 1 compared with number of road links inside IA
	Links length (Type 2)(m)	Total length of road links of Type 2 inside IA
	Links length (Type 1)(m)	Total length of road links of Type 1 inside IA
	Links density (Type 1) (m/ha)	Average length of road links of Type 1 per hectare
	Links density (Type 2) (m/ha)	Average length of road links of Type 2 per hectare

6. The integration of urban design into walkability in transit areas has been highlighted in existing research, but most existing studies are marked by ambiguity (Saelens et al., 2003a). However, Park (2008) did a composite walkability index in California to test the impact on modal shift to transit and walking behavior by dividing the walkability indicators into **two groups** of traditional transportation and urban design. The author believes that this kind of research can be a part of the new empirical foundation for future urban design theories, since little systematic measurements have been found to quantify urban design attributes of street level factors recently. The weight

values were calculated from the proportion of the respondents' choices for each walkability components. Even though the objectives seem compatible with the purpose in this paper, it is not possible for this study to match the work of Park (2008)'s where 52 path walkability indicators were measured for each of the 68 routes, and mapped by the survey respondents.

However, given the scale of the present study, the walkability components of Park (2008)'s can be interpreted and simplified as the indicators of walkability in this paper. The computed values for those **two groups** of traditional transportation and urban design can be used as two dimension to help structure the walkability index in table 2-6.

Table 2-6: Walkability in a case in California (USA)

Dimension	Indicators	Description
Traditional transportation	Sense of Safety (from traffic)	Sense of safety in pedestrian crossing affected by traffic speed
		Sense of safety in pedestrian crossing affected by crossing facilities
		Sense of safety in walking on the sidewalk
	Sense of security (from crime)	Sense of security because of existence of others
		Sense of security affected by visibility night
		Sense of security by visual surveillance from a nearby building
Urban design	Comfort	Sidewalk level-of-service & Continuity
		Buffering negative environmental effects
		Sense of street scale & enclosure
	Convenience	Ease of pedestrian crossing
		Easy access to local stores
	Visual Interest	Visual variety
		Visual attractiveness

7. It has been a common understanding that there are difficulties in capturing people's perceptions of the physical environment. Ewing and Handy (2009) produced 51 perceptual qualities based on the review of literature involving urban design and other fields such as architecture and psychology. Of the 51 perceptual qualities, eight were selected for further study based on the importance assigned to them in the literature, and they were: imageability, enclosure, human scale, transparency, complexity, legibility, linkage and coherence. The study however relies on former works in urban design and ends up with a consensus definition among the panel of experts from cross-sectional fields related to urban design. Due to the lack of access to experts in my study, it is important to refer Handy (2009)'s work that especially focuses on the importance of design dimension in building environmental-friendly pedestrian streets. A validation study is currently on the progress in New York City by using these eight pillars in table 2-7.

Table 2-7: Eight pillars of urban design produced by Ewing and Handy (USA)

Dimension	Indicators	Description
Urban design	Imageability	a place whose elements are easily identifiable and grouped into an overall pattern: Landmarks (singularity and location) & Sense of place (characteristic visual theme)
	Enclosure	Buildings, walls, trees, and other vertical elements. A room-like quality. The buildings become the "walls" of the outdoor room. The street and sidewalks become the "floor".
	Human Scale	Building details, pavement texture, street trees and street furniture; Moderate-sized buildings, narrow streets, and small spaces create an intimate environment; Information field should be scaled for offering a rich and coherent information at 5 km per hour
	Transparency	Physical elements that influence transparency include walls; windows, doors, fences, landscaping, and openings into midblock spaces.
	Complexity	The visual richness of a place, architectural diversity and ornamentation, landscape elements, street furniture, signage and human activity.
	Coherence	A sense of visual order. The degree of coherence is influenced by consistency and complementarity in the scale, character, and arrangement of physical elements.
	Legibility	The ease with which the spatial structure of a place can be understood and navigated as a whole, serving as reference points
	Linkage	Refers to physical and visual connections from building to street, building to building, space to space, or one side of the street to the other – that tend to unify urban space.

2.5 Conclusion and overview of a relevant walkability index applied to a TOD

Unlike past research where attention mainly focused on health or livable and lively neighborhood, the walking component is an under-researched topic in transport-related research and it needs further attention to understand determinant factors in walking environments (Schlossberg & Brown, 2004). Therefore, the cooperation of focus between two fields of health and transportation calls for an innovative solution to strengthen the assessment on walking environment and this is emphasized in this thesis. A walkability research needs to be applied within a TOD context rather than just referring to the general city plan.

Walkability indexes have been frequently used in physical activity research and related human behavior studies (Van Dyck et al., 2010). The methods and techniques that were used vary and no such single assessment tool can be designed to suit different environmental conditions (Moayedi et al., 2013). But at such an early stage of walkability assessment, it can help to examine the influence of the built environment on walking behavior. On the specific purpose of developing TOD and making more pedestrian-friendly environment, the combination of accessibility and urban design is explored and further described in the Chapter 3 on methodology.

Since walkability index is to be calculated for a clearly defined area, and to compare the relative performance across areas, GIS platform is a promising tool to quantify and visualize a walkable environment within a specific range around transit nodes. This will help in efficient evaluation of TOD projects. This will be achieved in the result chapter where the application of the index is shown.

Above all, an ideal and extensive list of walkability indicators can be overwhelming and some indicators from different authors have overlapping aspects, assumptions and ideas. In the process of collecting the indicators, the most cited and important ones were identified and can be re-organized according to my research purpose. The methodologies, however, differ based on the data availability and different situations in each type of study.

In the review of the literature in this chapter, several key themes emerged and have been organized in a conceptual framework in figure 2-2. There are three themes named as criteria at the top of the framework and their relative determinants listed with different colors according to different authors: **accessibility,** as the fundamental criteria of walkability from a transport perspective in a TOD context; the sense of **safety,** that reflects the basic needs when walking (people tend to prefer car-free areas and places with a low crime perception); the **design** factors that express the sense of comfort and convenience and other aesthetic aspects (i.e. greenery).

KEY THEMES OF PHYSICAL ENVIRONMENT

Accessibility	Safety		Urban Design	
	Traffic	Personal	Comfort & Convenience	Attractiveness
Directness	Street Crossing Considering travelspeed	Visual line of sight and street lighting	Weather protection	Physical interest and Amenities
Continuity	Pedestrian walking behavior	Streed lighting of road segment	Path location;Path slope	Pavement surface
Street Crossing	Pedestrian crossing behavior	Lighting of crosswalk	Sidewalk available width	Pavement condition & smoothness;
Pedestrian infrastructure	Type of crossing	Lighting	Street furniture	Street cleaniness
Obstacles	Crossing control	Building frontage transparency	Ramp convenience	Trees
Connetion	Sidewalk buffer width	Blind or walled path	Land uses	Amenities
Corner obstacles	Pedestrian crossing affected by traffic speed	Existence of others	Climate protection	Maintenance
Sidewalk Continuous	Crossing facilities	Visibility night	Path enclosure	Cleanlines
Vehicles parking in the sidewalk	Walking on the sidewalk affected by traffic	Visual Surveillance from nearby building	Coexist with other transport mode	Visual variety
Quantity of Accessible Paths	Number of road links	Transparency	Negative environmental effects	Visual attractiveness
Quantity of Impedance Paths	Links of type(%),length,density		Street scale & enclosure	Imageability
PCA/IPCA(%)			Sidewalk Level-of-Service & Continuity	Human scale
Impedance based Intersection density			Ease of Pedestrian crossing	Complexity
MPCA(%)			Easy access to local stores	Coherence
Nodes number density(m)			Enclosure	
Links number,density (ha/block)			Legibility	

Figure 2-2: Key themes of physical environment and determinants of walkability

Both qualitative and quantitative measures will be used within these themes (see Chapter 3 on methodology). As the most functional feature among the walkability research, the accessibility in the framework relates to the fundamental variables in transportation field to examine the proximity (such as the PCA reflects the actual distance to the transit nodes) and connectivity (such as the counting of obstacles and the percentage of intersections that measure the continuity) of the street network. The **safety** feature was divided into two aspects of *traffic* and *personal*, of which the traffic element includes safety on sidewalk and crosswalk affected by traffic speed and volume, as well as the facilities that support the safe crossing behavior. For the sense of safety that represents the personal issue, it refers to the sense of being away from the danger caused by others, as well as the presence of lighting and “eyes on the street”. Apart from the primary concern with controlling external appearance, the **urban design** has widened its range to cover broader environmental concerns such as comfort and convenience to give a more valuable legitimacy (Greed & Roberts, 2014) . The elements of *comfort* and *convenience* are combined together as one due to the similarities and thus confusion over definitions. The level of comfort also often shares the outcome of the convenience in most of previous research (Shove, 2003; Cambra, 2012). This combined element include concerns such as weather protection, conflict with other pedestrians on street, and, the amenities such as retail areas and street furniture. Another element ‘aesthetics’ has been difficult to be measured objectively in history, thus it is replaced by the word of *attractiveness* to get a more specific picture and serve the goal of the survey.

3 Methodology

This chapter presents the methodology guided by the research questions of how to define the immediate surrounding areas of the transit nodes and how will the indicators be measured in an index.

3.1 Delineating the study area

In typical TOD researches, the easy walking distance within a highly mixed area to public transport station is commonly between 400 and 800m buffer area (Galelo, Ribeiro, & Martinez, 2014; Dittmar & Ohland, 2004). Experts generally believed that transit riders will walk up to a quarter-mile to a bus stop and a half-mile to a train station (Litman, 2016). Other findings show significantly higher rates of transit use within one-quarter mile of a rail station than sites between one-quarter and one-half mile from stations (Dill, 2003).

The present study adopts a spatial scale of 400 meters to undertake the walkability assessment in a TOD area. This corresponds to a 5 minutes' walk. In the literature it was found that assessment of TOD areas are also done for a 10 minutes walking distance (800 meters). However, the analysis at the street level in which safety and design features are involved is often applied within the 400m radius. With the purpose of calculating a walkability index in a TOD context, the analysis has to base on the same level, in which the research objects need to be within the same catchment from the train station. Therefore, the overlapping area of the 400m buffer is chosen to be studied. Further research can explore the wider 800m buffer to get a more comprehensive understanding of TOD walkability for comparison. Figure 3-1 shows the location of two stations in Nijmegen city that are the case study for this thesis. It also shows the buffer zones of 400m in this study and 800m in potential walkability research. One of these two stations is located in the city center and another one is close to the Radboud University Campus, therefore, the differences in their users and locations can be important issues for a discussion.

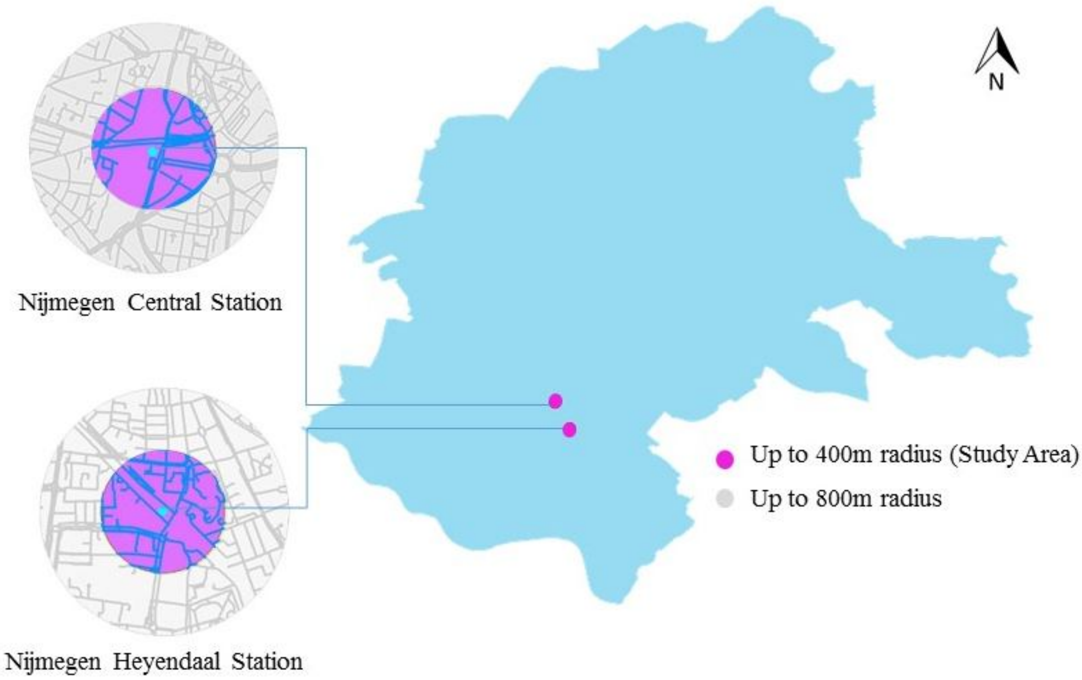


Figure 3-1: Study area, spatial scale of 400 meters

Walkability index is often based on a network analysis. This type of analysis is often classified into neighborhood-based scale (Dannenberg et al., 2005) and Meso scale (Cambra, 2012a), and they are either measured through a questionnaire survey or by the collected geographic data in terms of the street network. However, it is suggested to analyze the nearby environment at the edge of the catchment in spite of the boundary being set and visualized in ArcGIS. In other words, certain features that relate to the studied contents outside the study area are necessarily to be included in the analysis. For the purpose of involving the design dimension, the assessment should be made in accordance of micro scale for each of the single street segment. Each segment based on the pedestrian network can be studied by managing a spatial database in GIS according to the scores of walkability indicators.

3.2 Development of walkability index

A screening process was done to the potential indicators from the items of each key theme and a refined list of indicators in a form of index in a TOD context is presented in table 3-1. Indicators that present the similar characteristics of the physical environment in literature were merged into one and are appropriate for data collection in this study. The descriptions of how to measure the indicators are presented in the following sub-sections.

Table 3-1: List of refined indicators in a walkability index

Dimension	Criteria	Indicators
TOD Fundamental	Accessibility	IPCA
		Impedance based Intersection density
Safety	Traffic	Walking affected by traffic
		Segregation of the paths
		Crossing facilities
	Personal	Street lighting
		Visual surveillance
Urban Design	Comfort & Convenience	Climate protection*
		Sufficient sidewalk
		Access to local stores
		Path condition
		Amenities
	Attractiveness	Greenery

**The indicator of climate protection has been excluded because of the study limitations.*

3.3 Data Collection

The data used in this research has different sources:

a. Geographical data: Data for street network was obtained from Dutch Cyclist Union (Fietsersbond) routeplanner dataset in 2016.
b. Statistical data: Data for housing and buildings were obtained from Province Gelderland in 2012; others such as lighting and greenery were also obtained from Fietsersbond (2016).
c. Field data: Data on observation of environmental attributes was collected by own field trips during November 2016.

3.3.1 TOD Fundamental (Accessibility)

Accessibility was used as the criteria to quantify the TOD fundamental dimension. Two indicators are selected to quantify accessibility to TOD nodes by pedestrians: Impedance Pedestrian Catchment Areas (IPCA) and Intersection density.

Impedance pedestrian catchment area (IPCA)

Description: IPCA reflects the connectivity through the concentration of intersections. By showing the actual and path-based walking distance within a theoretical area, the pedestrian service areas are mapped for a 400m radius from the center of a train station (figure 3-2).

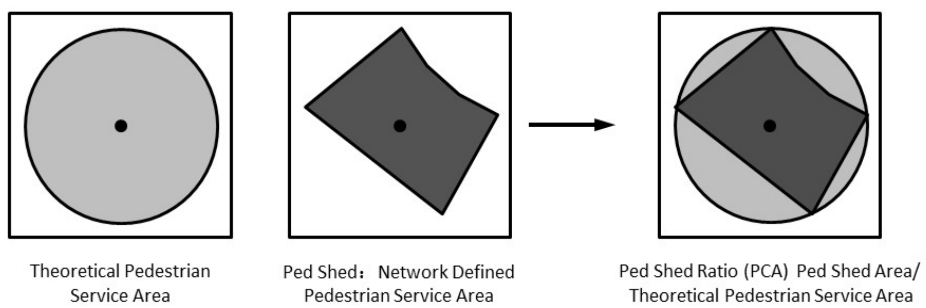


Figure 3-2: Scheme of PCA, Source: Schlossberg and Brown (2004)

Measurement: Ped Shed percentage between the Euclidean distance and the network distance. The impedance of freeways and pedestrian has dead ends would be removed when calculating the pedestrian service area. The more coverage of the network, the better the walkability in the zone. The basic information of street network such as bicycle lanes, main roads and freeways were classified through GIS. The results of the percentage are then divided into three levels:

- Level 0 (low): coverage is less than 20% within the 400m walking distance area
- Level 1 (medium): coverage is less than 60% but more than 20%
- Level 2 (high): coverage is more than 60%.

Data requirement: the pedestrian network was drawn from the Fietsersbond dataset (reference), by assuming that the road network should be accompanied by sidewalks (except for the tunnels that only exists in the central station area and are only for pedestrians).

Intersection density

Description: intersection density is measured by a percentage involving the number of intersections in the street/road network. The intersections were examined in a sense of accessibility, i.e., on how people perceive the intersection as barriers to the comfort or convenience.

Measurement: two approaches can be used to measure this indicator. The first is the percentage of the number of links to the number of nodes within 400m radius. The second is the percentage of street intersections that are available for walking divided by the sum of intersections and dead ends. The second approach was selected because of its usefulness for communities to evaluate new development towards street and road network. The latter one is more specialized on the identification of actual intersections among intersections with dead ends, in which the impedance based consideration can be reflected through taking into account pedestrian hostile roads with high volume and speed. Therefore, the latter one is adopted in this study in order to involve the concerns of barriers within a 400m radius.

- Level 0 (low): less than 20%
- Level 1 (medium): between 20% and 60%
- Level 2 (high): more than 60%

A scale is measured for the second approach, which can be as high as 0.6, which is assigned the score of 2 in this study for highly pedestrian connected street network, and as low less than 0.2, which is assigned the score of 0 for poorly connected, others the score is 1. The former one

Data requirement: the same spatial data as used for measuring IPCA.

3.3.2 Safety (Traffic)

Three indicators were used to measure safety of pedestrian in relation to motorized traffic:

Walking affected by traffic

Description: most studies suggest that by decreasing 10km/h travel speed, the travel time may increase by 5% (J. Fotheringham, N. Symmons, M. Corben, 2008). There is an instrument that called "Areas 30" where the zones have the limited speed of 30 km/h. It was implemented first in Netherlands, France and Germany in the 1980's. The safety effects of 30km/h are treated as positive after an evaluation of impact on 15 municipalities in the Netherlands. During the 1990's, it spread throughout roads or in zones within built-up areas in Europe (Vis, Dijkstra, & Slop, 1992). A thorough literature review published by U.S. Department of Transportation, National Highway Traffic Safety Administration (reference, 1999) shows that the impact of travel speed is struck at 32 km/h, where the pedestrian mortality is less than 5%, whilst at 50 km/h is about 50%.

Measurement: there are two levels according to the standard travel speed, which the speed is less or equal to 30km/h is high level (safer for walking) and speeds over 30 km/h is the lowest level (less safe for pedestrians).

Data requirement: speed restriction of each street within the buffer area

Segregation of the paths

Description: generally, in the Dutch context, the streets can be separated into three parts: roads, bicycle lanes and sidewalks. This indicator aims to examine whether the performance of segregation in roads can provide a safe walking environment. Figure 3-3 shows examples of the path segregation in European cities. However, the Figure on the right exemplifies that there could be co-existence of walking and cycling on one path, especially when pedestrians tend to step to the central positioned bus stop.

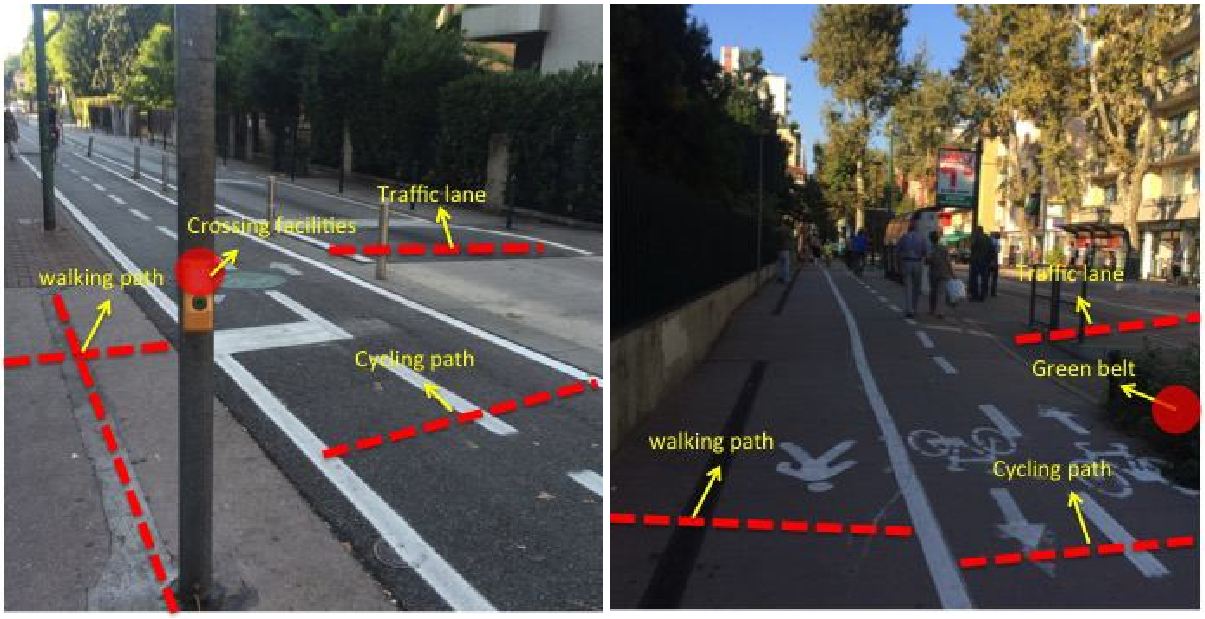


Figure 3-3: Examples of segregated paths in Italy

Measurement: three levels, as such:

- Level 0 (low): sidewalk shared with cars
- Level 1 (medium): sidewalk shared with bicycles
- Level 2 (medium-high): sidewalk segregated from roads and bicycle lanes
- Level 3 (high): sidewalk well segregated with barriers (green belt or other street furniture)

Data requirement: OSM/conduct a fieldwork

Crossing facilities

Description: the crossing facilities are defined as the marks and signs on the street or along the street that remind the pedestrians to follow the instructions that prevent from the misleading crossing behaviors. In the Dutch context, there are three types of crossing facilities at junctions, which are zebra lines, stop and yield lines (usually in the style of triangle) and vertical signs (including traffic lights) along the street. Figure 3-4 shows the ideal Dutch junction design in general.

Figure 3-4: Crossing facilities in Netherlands

Measurement: five levels, as such:

- Level 0: crossing point has no facilities
- Level 1: crossing point has one facility
- Level 2: crossing point has two facilities
- Level 3: crossing point has three facilities
- Level 4: no need of crossing at crossing point

in which the lowest level has no presence of crossing facilities, and follow the path until having all the four crossing facilities was assigned 3 and the highest level of 4 means no need of crossing that safety is very high.

Data requirement: conduct a fieldwork in the evening/OSM

3.3.3 Safety (Personal)

Two indicators were used to measure personal safety: street lightning and visual surveillance.

Street lighting

Description: According to the description in Fietserbond (2016), streets that have reasonable lighting are illuminated by having light towers shorter than 8 meters and not more than 60 meters apart; or if light towers are higher than 8 meters, then they are not more than 80 meters apart.

Therefore, the distance of the light towers and their reach of light on the ground are considered to be the identification of bad and good condition. After the discussion of how the lighting levels are normally divided according to citizens' perception, three conditions are schemed in figure 3-5, showing the walkers intend to judge the good or bad lighting by what they see the light beam on the ground and in turn the sense of safety to their personal experience.

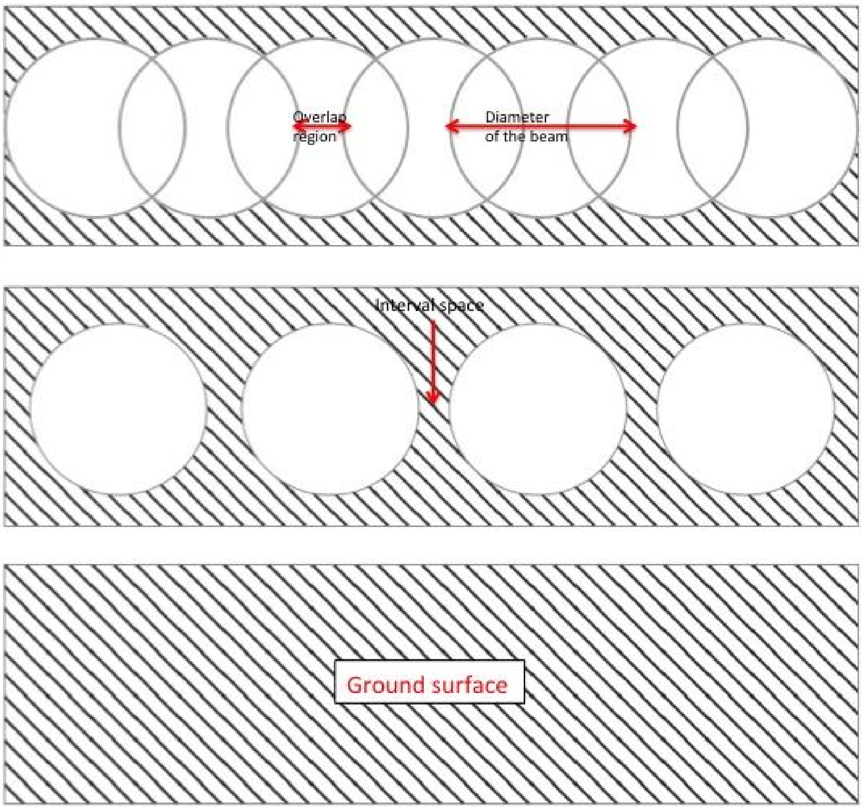


Figure 3-5: Reach of the light

Measurement: three levels, as such:

- Level 0 (low): no lighting and dark at the same time
- Level 1 (medium): lighting beam, but shadows do not overlap (insufficient lighting or just with lighting)
- Level 2 (high): plenty of and continuous lightning, shadows overlap (good lighting)

Data requirement: the secondary data regarding the lighting condition were found in the dataset of Fietsersbond (2016). However, there are lack of comprehensive information in this dataset because of its bicycle focus. A fieldwork was done to complete the data.

Visual surveillance

Description: the level of the visual surveillance manifest the condition that the existence of windows instead of a blind/ walled path would reduce the sense of safety when walking along the street. Therefore, the texture of buildings such as windows and their level of transparency is the main concern to create a feeling of "eyes on the street". Here the ambiguity of the perceptions for street enclosure has overcome by using this more specific indicator, which also describes the wall effect between people and buildings. The level of safety was also assumed in this case on the windows along the ground floor and if these windows are served for residential/ office purpose, where less people care to watch on the street, or commercial purposes, where people are inside having their leisure time and looking around. Figure 3-6 gives the examples of the two occasions in Enschede, Netherlands.

Figure 3-6: Windows of residential/office building (left) and of commercial buildings (right) in Netherlands

Measurement: the lowest level is the situation of walled buildings along the street, causing blindness from the inside; the medium level is the situation of office/residential buildings, with windows; and the highest level is the situation that commercial purpose such as stores and shops with windows on their buildings. The research range will be limited to the ground floor. In the fieldwork, some mixed blocks were categorized by the identification of the dominant building type.

Data requirement: Acquired through fieldwork.

3.3.4 Urban design (Comfort and Convenience)

Five indicators were selected to measure this dimension:

Climate protection

Description: the negative weather can be relieved by trees planted along the street, as well as the protection from buildings that have long overhang eaves preventing from wind or rain. Figure 3-7 shows the different building profiles in wind-driven weather and their potential design factors that affect the comfort and convenience of pedestrians under poor weather conditions. The building with no eave shows none of protection and the longer eave the more protection.

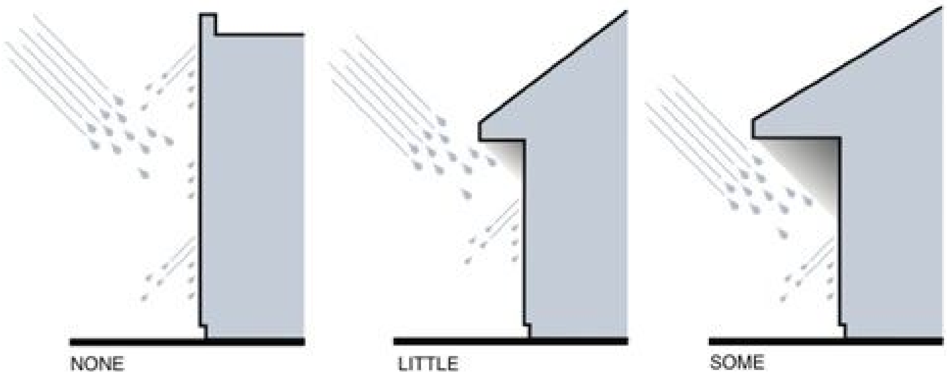


Figure 3-7: Buildings in bad weather

Measurement: the lowest level is the situation where there is no protection along the street; the medium level is the situation where there is medium protection along the street; and the highest level is where there are plenty of protections. It is noteworthy that this indicator has challenges to be well categorized in some cases: for example, in an area that has the unpredictable weather, or has the dramatic differences among seasons. These uncontrollable factors highly rely on the meteorology and its influence on tree planting and so on, so that the climate indicators are difficult to classify merely during periods of time. Based on this reason, this indicator was not included in the present study, although it is acknowledged as being important in the context of walkability.

Sufficient sidewalk

Description: the sufficient sidewalk depends on whether there are obstacles in the way, forcing pedestrians to deviate from them.

Measurement: the obstacles need to be identified and categorized from the lowest level to the highest level. The lowest level is when there are obstacles forcing people to leave the sidewalk and the highest level is no obstacles. The medium level thus is the situation that even obstacles exists but the available width is still sufficient for the pedestrian to pass by. The assumption is that the surface condition of each road segment is constantly. However, if some exception exist the dominant level would be adopted. Figure 3-8 shows the typical obstacles that exist in most of the residential areas.

Data requirement: Acquired through fieldwork.

Figure 3-8: Examples of Obstacles on sidewalk in Suffolk

Local stores

Description: this indicator examines the convenience for pedestrians to access local stores and acquire their daily essentials from stores nearby.

Measurement: The presence of the stores within the catchment is measured to level the 0 for non-exist of stores and 1 for the existence.

Data requirement: BAGverbl data of points

Path condition

Description: the presence of the paving materials and its smoothness that makes an easy walking experience on the surface of the pavement decide the level of this indicator. The existence of the pavement that was designed for and meets the basic needs of walking should be the benchmark for this indicator.

Measurement: Two levels of presence (level 1) and no presence (level 0) of the paving material on the sidewalk, the pavement should be built for the purpose of walking convenience. The unit situation on one sidewalk segment would consider the dominate one. Figure 3-9 shows the Portuguese pavement that is suitable for walking and the U.S. example of soil pavement that is not suitable for pedestrians.

Data requirement: Acquired through fieldwork.

Figure 3-9: Examples of path condition in Portugal and U.S.

Urban furniture

Description: the presence of urban furniture such as benches, trash bins, ATMs that are convenient for the pedestrians when they are walking to train stations.

Measurement: two levels of presence (level 1) and no presence (level 0) of the amenities on the sidewalk.

Data requirement: Acquired through fieldwork.

3.3.5 Urban design (Attractiveness)

One indicator was used to quantify urban design aspects in relation to attractiveness. Greenery was selected because the availability of the data resource in terms of attracting pedestrians. There are more indicators could be added except for the natural landscape that gain the attention of pedestrians, however due to the limitation of the fieldwork, the researcher couldn't build a sufficient database that includes all detailed aesthetic aspects on sidewalks. Therefore, the indicators such as (type of pavement or design of the furniture) were not considered in this study.

Greenery

Description: the existence and volume of the greenery along the street were categorized: the lowest level has little green, medium level has some greenery and high level has plenty of green.

Measurement: the secondary data in Fietsersbond (2016) has the classification of how well the greenery is distributed to the street segments, and therein lies the sidewalk segments. However, because not all streets have the greenery information in the dataset, a fieldwork was done for completeness. Figure3-10 gives the examples of greenery that can be based on both natural scenes and landscape design in building, for example, the vegetable gardens along the street.

Data requirement: Fietsersbond, and completed through fieldwork.

Figure 3-10: Examples of greenery along sidewalks in Japan and France

The final lists of indicators and their levels with their brief explanation are collected in the table 3-2. There are two stations in Nijmegen selected and the study was held on within their 400m buffer around train stations. Each street segments within the areas were examined and leveled, some of the indicators were scored by mean value due to there are two sides of the walking path having mixed situation for one unit of street, or only one side of the path having the mixed blocks.

Before conducting the fieldwork in Nijmegen, the researcher prepared two checklists and two printed maps in order to record the observation according to their own walking experience (for further information on checklists and maps see ANNEX A and ANNEX B). The checklists and maps are obtained from the attribute tables of street network and their visualizations in GIS with each road is marked by their unique numbers. Some indicators such as ‘sufficient sidewalks’ and ‘local stores’ can almost rely on the information from OSM. However, there are several roads do not compatible with the information from the secondary data of those two providers. Therefore, most of the indicators should conduct a further investigation in field in order to get an exhaustive description and results.

Table 3-2: Walkability Criteria, indicators and their levels

Dimension	Criteria	Indicators	Levels	Explanation
TOD Fundamental	Accessibility	IPCA	0	less than 20%
			1	between 20% and 60%
			2	more than 60%
		intersection density	0	less than 20%
			1	between 20% and 60%
			2	more than 60%
Safety	Traffic	travel speed	0	more than 30km/h
			1	less than 30km/h
		segregation of the paths	0	shared with cars
			1	shared with bikes
			2	segregated
			3	segregated with barriers
		crossing facilities	0	no facilities
			1	one of (zebra, triangle and vertical signs)
			2	two elements included
			3	three elements included
			4	no need of crossing
	Personal	street lighting	0	no lighting
			1	with lighting
			2	good lighting
		visual surveillance	0	blind
			1	windows (offices)
			2	windows (shops, commercial service)
Urban Design	Comfort & Convenience	climate protection*	0	no protection
			1	medium amount of protection
			2	plenty of protection
		sufficient sidewalk	0	obstacles forcing people to leave the sidewalk
			1	even obstacles exists but the available width is still sufficient
			2	no obstacles
		local stores	0	no stores
			1	have stores
		path condition	0	no paving materials and not smooth in this segment
			1	with paving materials and easy to walk
		urban furniture	0	no amenities
			1	with amenities
	Attractiveness	greenery	0	no green
			1	little greenery
			2	with greenery
			3	plenty of green

3.4 Application of the walkability index

Given these arguments, a **base model** was developed, with indicators assigned with the same weight under their respective criteria. In case a criteria is decomposed in various indicator, the weight is equally distributed as shown in Table 3.4. The final score of the walkability index in an area can be obtained by the sum of weight*score.

Table 3-3: Base model of assigning weights

Criteria	Weight			Indicators
Accessibility	100	50	0.1	IPCA
		50	0.1	intersection density
Traffic	100	33.3	0.0667	walking affected by traffic
		33.3	0.0667	segregation of the paths
		33.3	0.0667	crossing facilities
Personal	100	50	0.1	street lighting
		50	0.1	visual surveillance
Comfort & Convenience	100	25	0.05	sufficient sidewalk
		25	0.05	local stores
		25	0.05	path condition
		25	0.05	urban furniture
Attractiveness	100	100	0.2	greenery
TOTAL	**500**	**500**	**1**	

4 Results

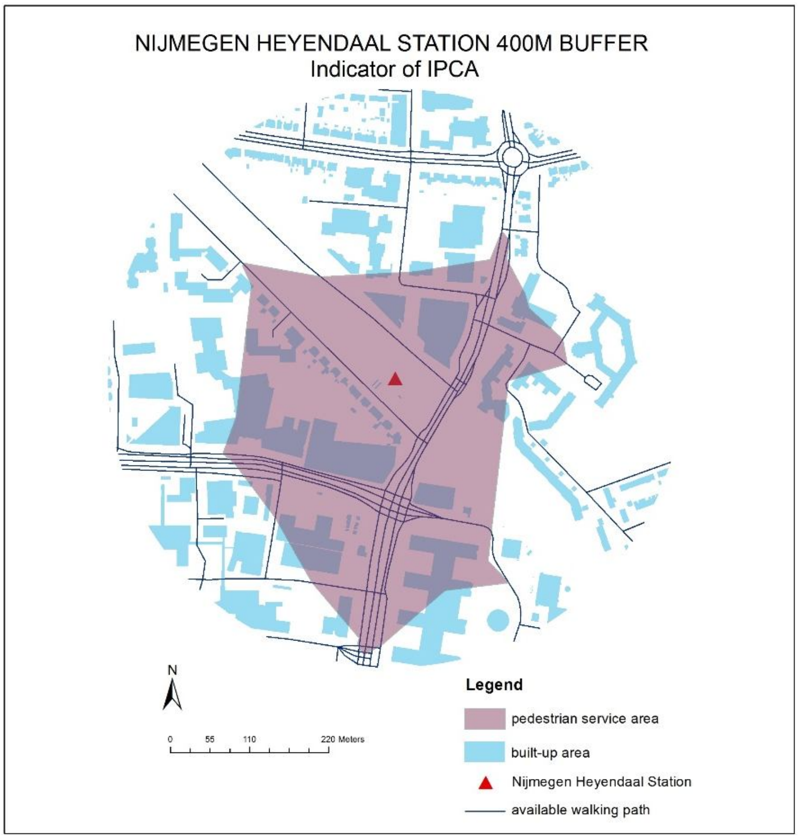
This chapter contributes to the research objective by answering the questions of how the refined indicators can be introduced in the local context and how to visualize the walkability indicators in GIS and walkability indexes among the studied transit nodes. In the conclusion part, the question about comparison and analysis between the transit nodes in terms of walkability index will be answered. This chapter explores the results from the fieldwork, whereby the developed index of walkability in TOD nodes is applied to the stations of Nijmegen Central and Nijmegen Heyendaal. Each indicator from the refined list of indicators is applied to the street network and marked by using different colors in maps produced by ArcGIS 10.1. For the methods of assigning levels to the indicators of each sidewalk, the researcher used the percentage to measure and level the accessibility criteria within the defined area, and the level of impact method to assign levels to other indicators. The percentages used to level the IPCA and intersection density are given in tables that show how levels were used to, compare indicators between stations. Following the results of walkability index of the two stations, this chapter gives two sets of visualization to see the differences among walkability indicators and the defined five criteria by using radar and bar charts. The final section of this chapter includes a discussion on the applicability and usefulness of the index in measuring walkability around TOD stations.

4.1 Measurement results of the walkability indicators

4.1.1 Accessibility - IPCA

Impedance Pedestrian Catchment Areas represent the actual area that can be covered by walking within the 400 meters buffer. Impedances, such as highways, tunnels or other such areas that do not allow pedestrians, are removed. With the ArcGIS Network Analyst extension, service areas around any location on a network can be found. A pedestrian service area is a region that encompasses all accessible walking paths within a theoretical area. In this case, a catchment of the 5-minute service area (400m around the train station) on the network includes all the streets for walking that can be reached within five minutes from that point of station.

The service areas created by the tool of Network Analyst in ArcGIS help to evaluate the criteria of accessibility by identifying how accessibility varies with impedance. Once the areas are created, the proportion of how much area is served for the walking within the catchment can be identified. The following figures illustrate how the two stations in Nijmegen fare with regards to IPCA.



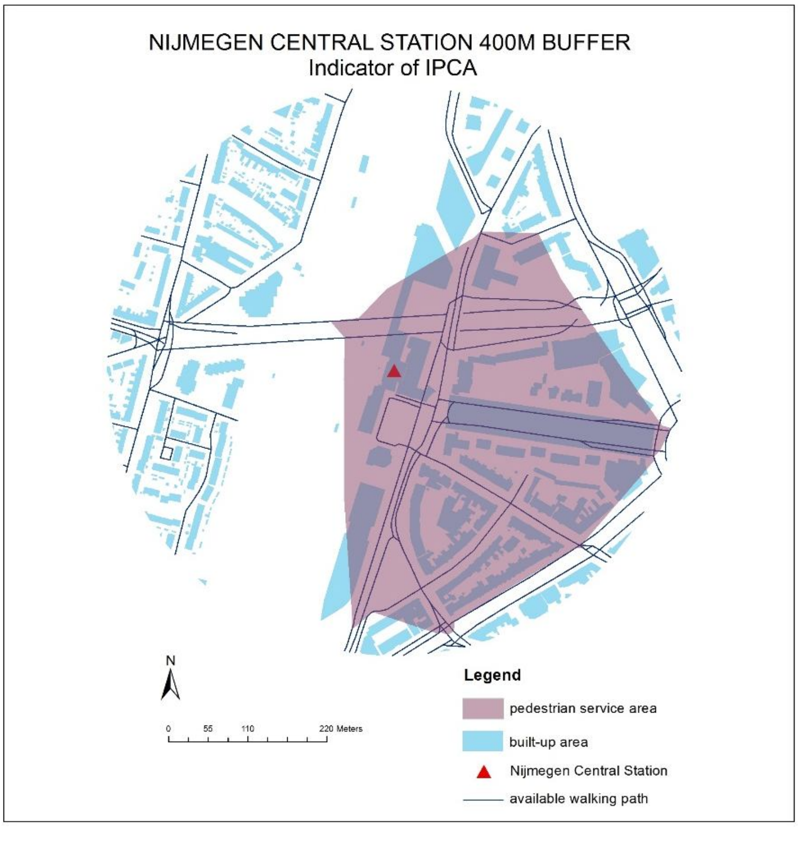


Figure 4-1: Indicator of IPCA

Table 4-1: Level percentage of IPCA

IPCA	IPCA	Area	Percentage	Level
Nijmegen Central	1761	5024	35.05%	1*
Nijmegen Heyendaal	1671	5024	33.26%	1

**There are three levels of IPCA. Level 1 indicates a percentage between 20% and 60%.*

By removing the high-speed roads from street network that do not allow walking, for example the most central parts of 'Tunnelweg' that are only for motorized vehicles, the final pedestrian catchment area (IPCA) within 400m around the two stations has been calculated. Based on the selected available walking paths, the IPCA percentage in Nijmegen Central station is 35.05%, and in Heyendaal station the percentage is 33.26% (table 4-1). Figure 4-1 shows how the coverage of pedestrian service area is distributed. According to the assigned percentage, the medium level of IPCA within the two stations is 1 because it falls between 20% and 60%.

The percentages reveal that there is not much difference regarding pedestrian service area occupied within the two areas. However, Figure 4-1 shows that the coverage in purple color tends to concentrate if there is no gap or blank space in between. This might be because of the gaps that cause difficulty for pedestrian traffic. For the central station, the gap connected by tunnels across the area is much bigger than the one within the Heyendaal station. Thus coverage deviates from the gap and concentrates on the eastern part of the buffer. Therefore, the western part of the buffer might not be explained as the area with low walkability but it is important for the purpose of heading to the train station. On the eastern side of Heyendaal station, the coverage is affected by the gap as well, but this plays a smaller influence because the station is located inside the gap and neutralizes the imbalance.

4.1.2 Accessibility: Intersection Density

The indicator of intersection density contributes to the criteria of accessibility to examine the existing choices that pedestrians can make in order to arrive at their train station within a specific area. Therefore, it is an indicative of the opportunities that are available for pedestrians to improve the efficiency in their trips. This indicator is also impedance based, making sure that all the streets involved are allowed for walking. The percentages reveal the actual number of intersections for pedestrian-only, and the intersection density within the 400m buffer.

The percentages in the table 4-2 are the result of counting the number of intersections available for walking to the sum of all intersections/junctions and dead ends in these two areas. Since the intersection density for both the stations in more than 60%, both stations were assigned the level 2. It also indicates that street network around both stations are well-connected for pedestrians. The Figure 4-2 describes how the intersections are counted based on the exported maps from ArcGIS and with all the nodes identified.

Table 4-2: Level percentage of intersection density

Intersection Density	intersection	Junction + dead ends	Percentage	Level
Nijmegen Central	151	222	68.02%	2*
Nijmegen Heyendaal	124	206	60.19%	2

**There are three levels of intersection density. Level 2 indicates the percentages more than 60%.*

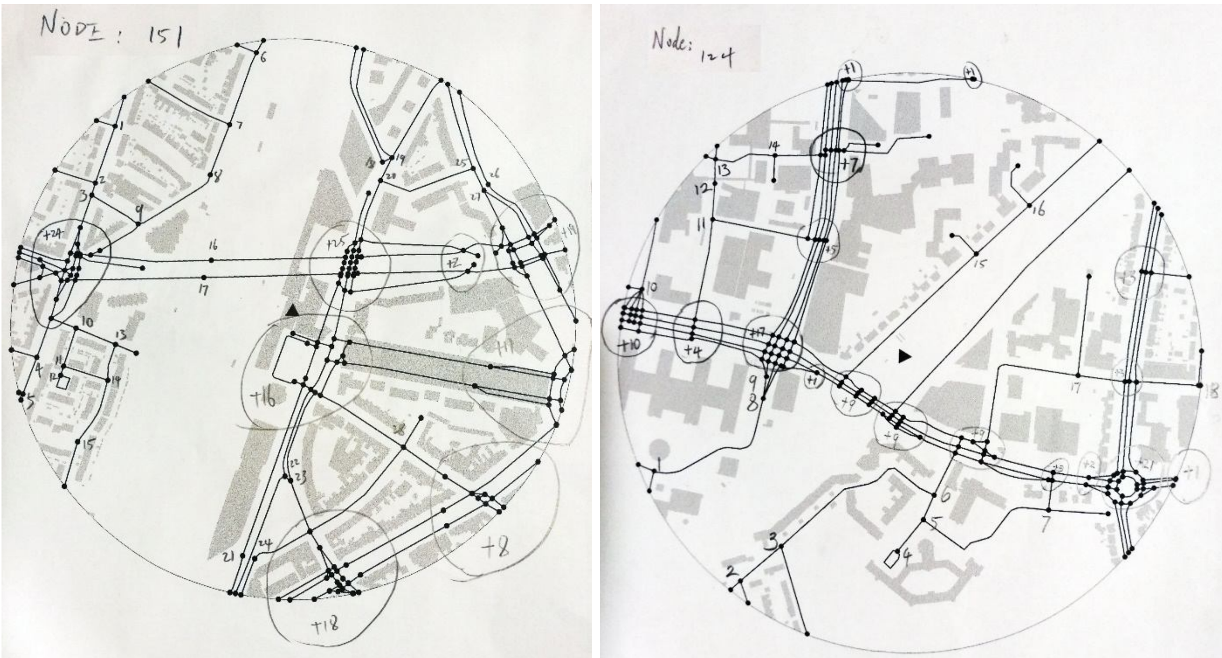
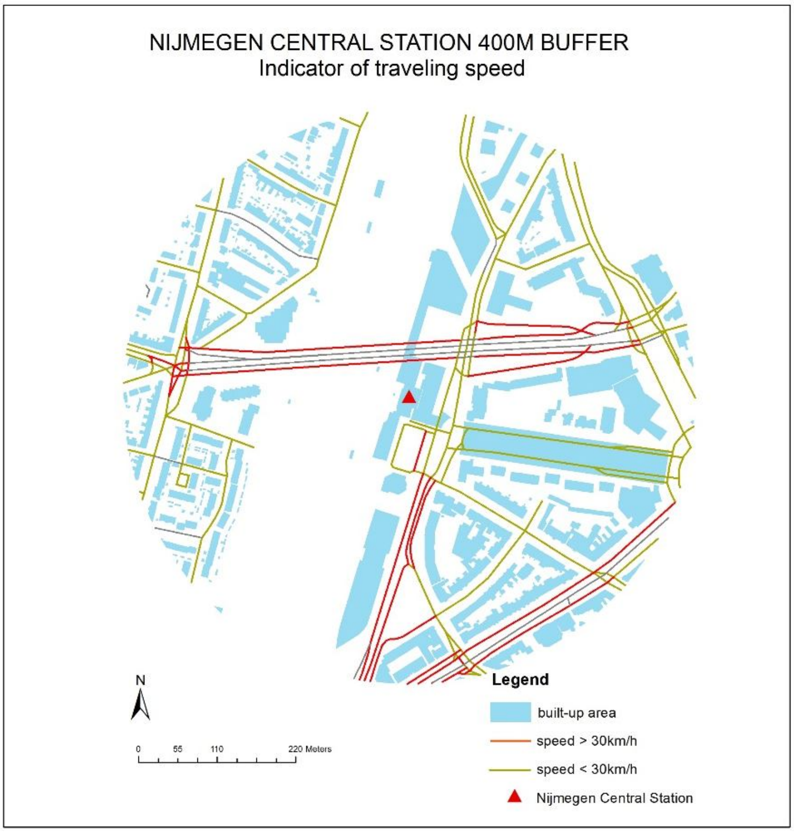


Figure 4-2: Counting intersections during fieldwork

4.1.3 Safety: Walking affected by traffic

Walking affected by traffic indicates how the travel speed on the roads affects the sense of safety when pedestrians walk on the sidewalks. From the perspective of pedestrians, car-free zones would be ideal that ensure complete safety. Two levels are set according to the speed limit signs of under and above 30 kilometers per hour. The following figure 4-3 demonstrate the two levels in red and green around two stations.



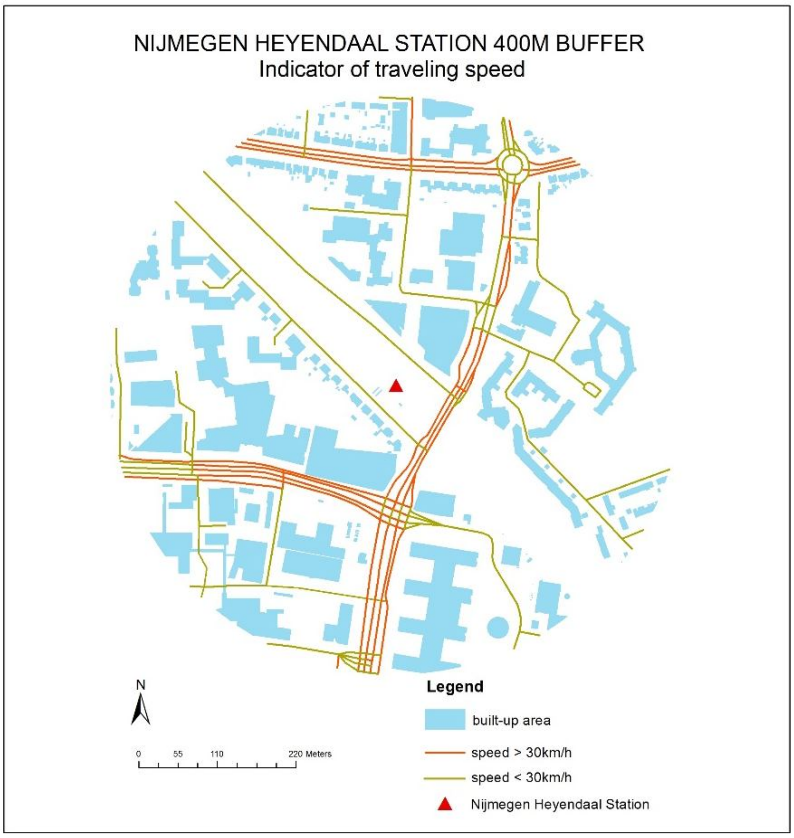


Figure 4-3: Indicator of Speed limits on streets

Table 4-3: Level percentage of travel speed

Travel Speed	Description	Percentage	Level
Nijmegen Central	more than 30km/h	25.45%	0
	less than 30km/h	74.55%	1
Nijmegen Heyendaal	more than 30km/h	43.98%	0
	less than 30km/h	56.02%	1

Level 1 means the allowed travel speed for cars on this road is less/ equal to 30km per hour, and the others of higher speed are assigned 0. From the table 4-3 above, it can be seen that the area around central station has higher percentage of level 1, compared to lower percentage of level 1 in Heyendaal area.

The results can be explained by the different facilities that area available around the central station and lead to higher volumes of different kinds of pedestrians. More education-oriented facilities around Heyendaal station area, on the other hand, limit the types of users. Upon observing the resulting maps in Figure 4-3, bigger blocks (size of the buildings) and less residential areas in Heyendaal station area can explain why higher speeds are allowed for the sake of convenience. Figure 4-4 shows street signage of speed limit.

Figure 4-4: Street signage of speed limits in Heyendaal

4.1.4 Safety: Segregation of paths

The segregation of the path provides higher safety to pedestrians. The Dutch society is known for being very bike-friendly, and almost every street includes bike lanes, but sidewalks also require space to separate pedestrians from the car flows in the middle and bikes passing by next to them. The indicator of path segregation divides the road condition into 4 levels that measure the sense of safety for pedestrians.

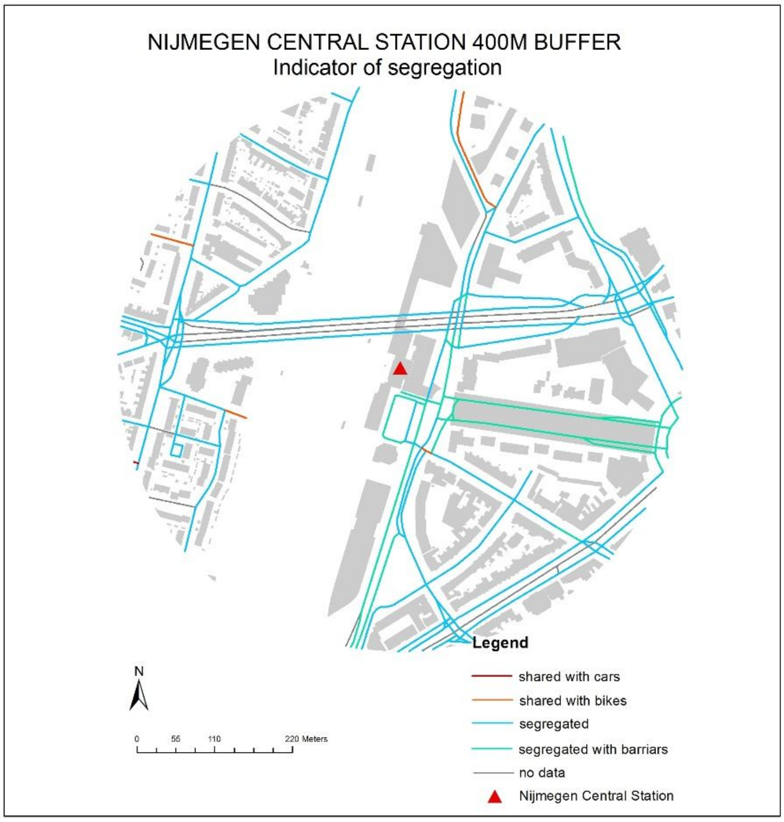


Figure 4-5: Indicator of segregation in Nijmegen Heyendaal

Table 4-4: Level percentage of segregation

Segregation	Description	Percentage	Level
Nijmegen Central	shared with cars	0.36%	0
	shared with bikes	1.82%	1
	segregated	68.73%	2
	segregated with barriers	17.09%	3
	no data	12.00%	No Data
Nijmegen Heyendaal	shared with cars	4.56%	0
	shared with bikes	2.49%	1
	segregated	80.08%	2
	segregated with barriers	9.13%	3
	no data	3.73%	No Data

In figure 4-5, the levels of segregation are divided into four and using the color from red to light green, standing for the degree of path segregation from the lowest level of 'shared with cars' to the ideal level of 'segregated with barriers' (greenbelt or other sketches). The table 4-4 presents each four levels according to each train station and the most frequent found paths are segregated, in both of the stations.

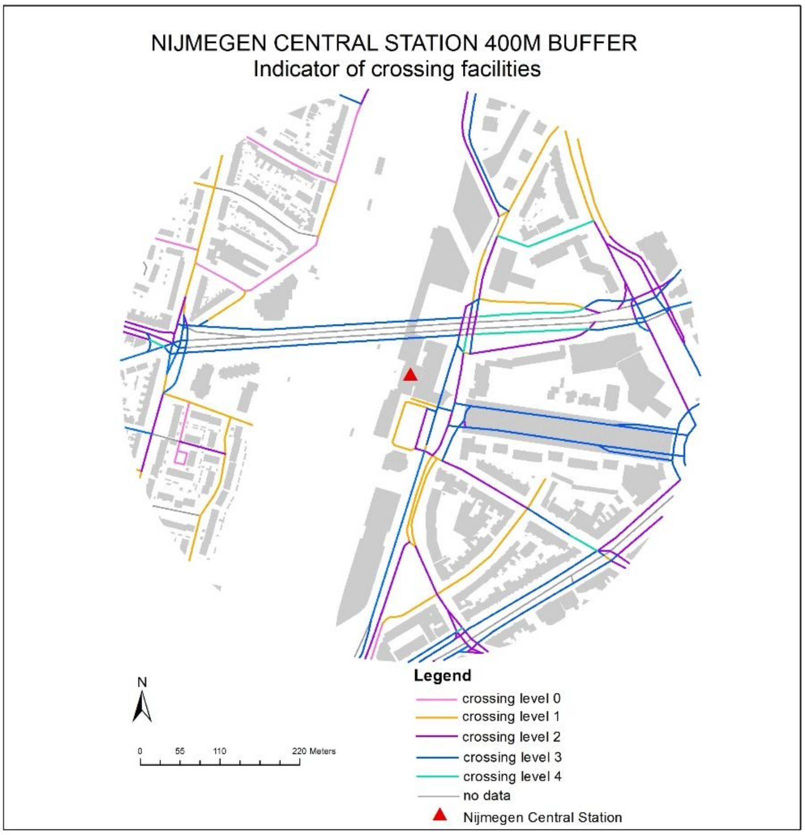
For the central station, most of the roads are segregated and from the map it can be seen that such ideal types of roads with walking paths are concentrated near the central station. For example, the 'Van Schaeck Mathonsingel' is specifically built for the pedestrian environment to create a central point of influence. This location is a walker's Paradise so that daily errands do not require a car (Figure 4-6). Around the Heyendaal station, the area has curved roads that emphasize the landscape and have segregation as well. Additionally it has higher percentage of segregated roads partly because of the bigger block size in this area.

Streets of no data are those streets for which the researcher found no sidewalks or where the street location was not possible to identify, based on the available secondary data. But in the central station most of these 'no data' streets are tunnels where no pedestrians are allowed to pass. Therefore, the streets that the researcher was not able to reach were assigned 'no data', and in such situations in the following sections it will be the same.

Figure 4-6: Van Schaeck Mathonsingel at Nijmegen Central Station

4.1.5 Safety: Crossing Facilities

The crossing facilities remind pedestrians to watch their steps when crossing the streets and remain safe from the complicated traffic movements at an intersection. The numbers of facilities at the two ends of one street were averaged to obtain the mean value for that street and then the corresponding levels were identified. There are three types of facilities involved in this case, while the highest level indicate there is no need of crossing behavior that ensure the complete safety at this point.



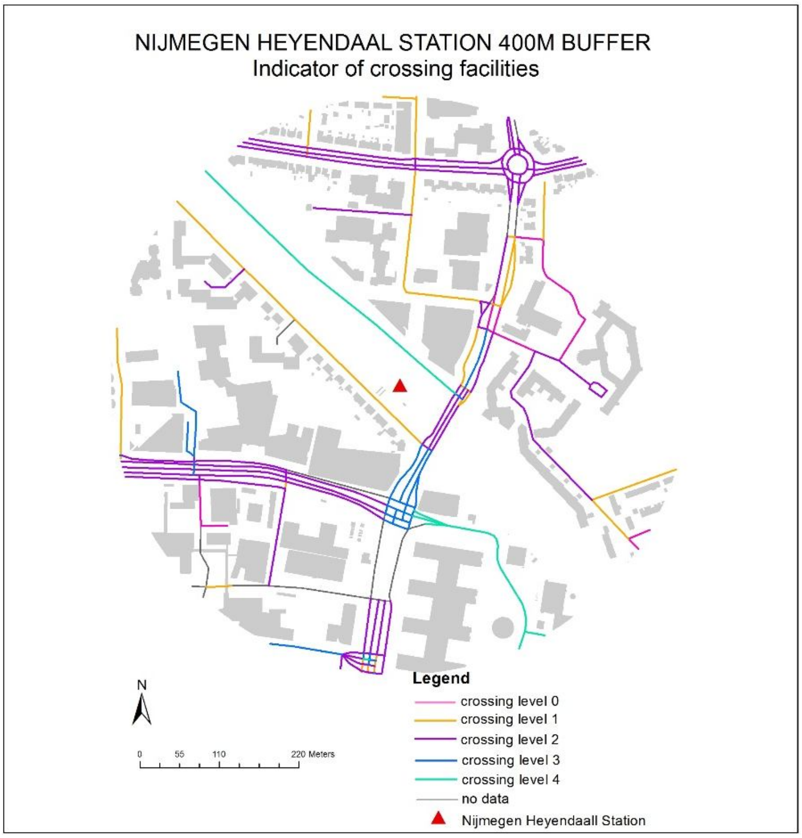


Figure 4-7: Indicator of crossing facilities

Table 4-5: Level percentage of crossing facilities

Crossing Facilities	Description	Percentage	Level
Nijmegen Central	no facilities	3.27%	0
	one of (zebra, triangle and vertical signs)	13.45%	1
	two facilities included	28.36%	2
	three facilities included	40.36%	3
	no need of crossing	2.55%	4
	no data	12.00%	No Data
Nijmegen Heyendaal	no facilities	4.56%	0
	one of (zebra, triangle and vertical signs)	16.18%	1
	two facilities included	48.13%	2
	three facilities included	19.50%	3
	no need of crossing	1.09%	4
	no data	3.27%	No Data

The level results of each street were changed into five items except for the ‘no data’ showed in figure 4-7 by using different colors. The figures in the table 4-5 have been rounded off to the integer numbers, because a unit of street has two situations at both ends. The originally defined numbers represent the number of crossing facilities including vertical signs, zebra lines, and surface marks. In other words, the street which has three facilities simultaneously would be classified into the level 3. The level 4, however, represents a situation where there is no need, or it is impossible to cross the street. The highest level implies safety since it is least affected crossing behavior. The scheme 4-8 illustrates how the levels were assigned to each street and the score for a street is the average number of both ends. Decimal numbers, were avoided in order to keep a smaller and organized result for the convenience of calculation.

The central station is found to have more complete crossing facilities within the study area. Besides the extreme situations of no facilities and no need of crossing, the level 3 applies to nearly half of all the crossings around central station, but only less than 20% of crossing around Heyendaal station. About half of all streets around Heyendaal station have an average of two facilities. It is difficult to say if it is because of the heterogeneity of crossing facilities in high mobility areas such as central station or for station areas with a relatively stable population from university and nearby hospital in the Heyendaal area. But the numbers prove that the difference originated due to the location and its related functions.

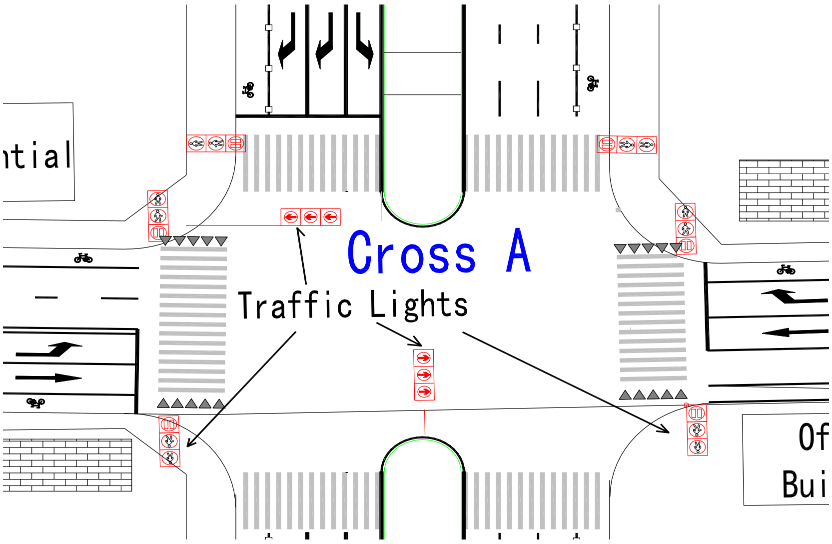


Figure 4-8: Scheme of elements for crossing facilities indicator

4.1.6 Safety: Street lighting

Basically there are three levels of street lighting - no lighting, insufficient lighting (with lighting) and the continuous well-lit streets (good lighting). The data collected is based on the secondary data provided by Fietsersbond (2016), also the observation during fieldtrip.

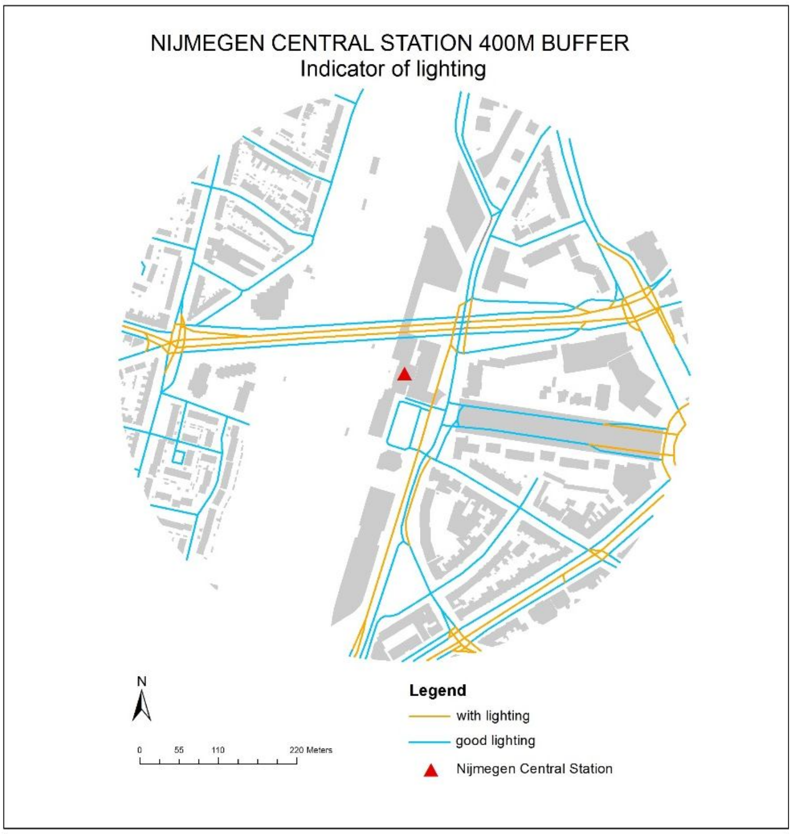


Figure 4-9: Indicator of Lighting

Table 4-6: Level percentage of lighting

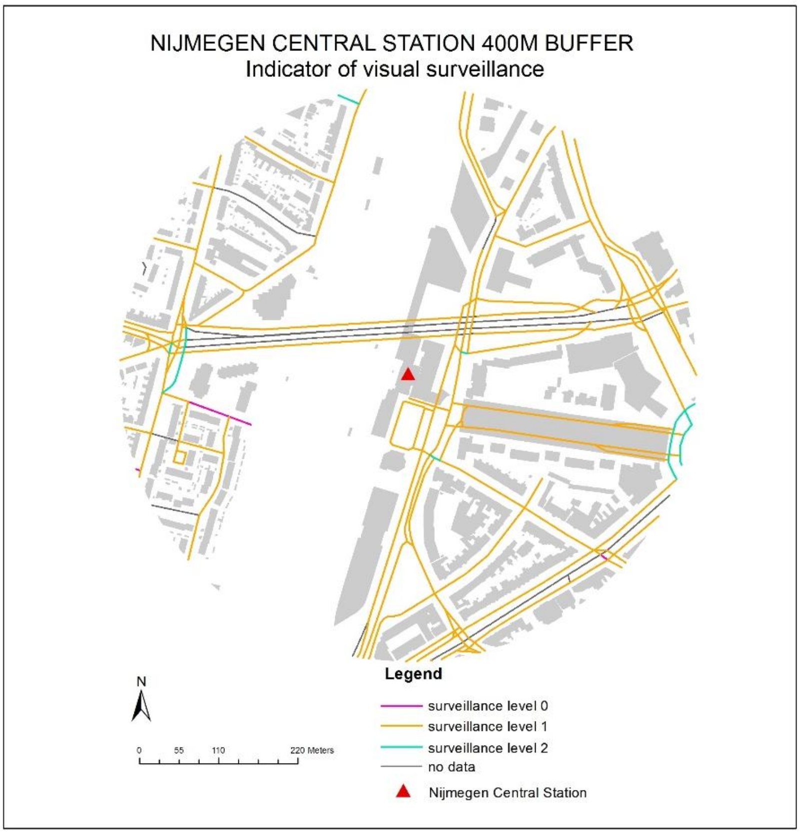
Lighting	Description	Percentage	Level
Nijmegen Central	with lighting	48.73%	1
	good lighting	49.82%	2
Nijmegen Heyendaal	with lighting	65.15%	1
	good lighting	34.85%	2

The lighting condition in both station areas is generally good. There were almost no streets without lighting (figure 4-9). The data collected, illustrated in table 4-6, are the streets with 'good lighting' were given the level of 2 and the rest went to the lower level of 1 of 'with lighting', which some of them are limited illumination that only has lighting at intersections, or the distances between the light poles are larger. However, none of these roads are equal to the level 0 of 'no lighting'.

Lighting conditions at the roundabout are also affected by the other light units, such as ground lighting facilities. Even though such situation was not classified in the good ones, the percentage numbers reflect the better lighting systems in central station area. Most of the residential areas offer continuous lighting on both sides of the walking path even though there are few commercial purpose buildings and low population among these smaller blocks.

4.1.7 Safety: Visual Surveillance

The visual surveillance is an indicator developed to measure the personal criteria feeling safety on the streets knowing that you are being watched by other people in the nearby buildings. The following maps give three levels of visual surveillance but for scoring, the numbers are averaged and rounded-off due to the mixed situation on streets. Similar mixed measurement was used for the indicator of crossing facilities.



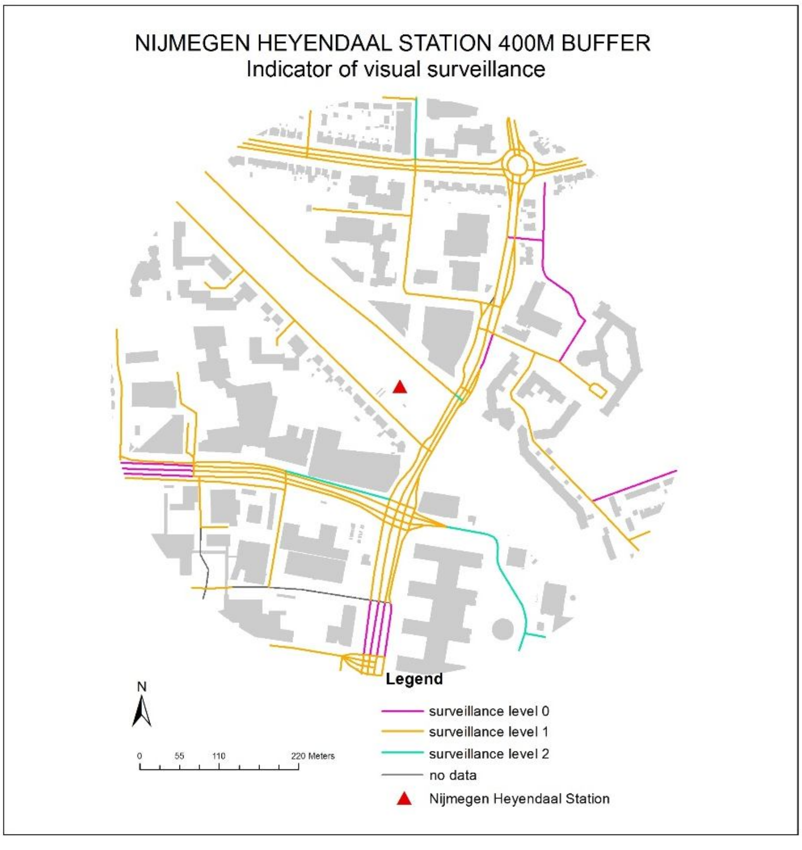


Figure 4-10: Indicator of visual surveillance

Table 4-7: Level percentage of visual surveillance

Visual Surveillance	Description	Percentage	Level
Nijmegen Central	blind	1.45%	0
	windows (offices)	79.64%	1
	windows (shops, commercial service)	6.91%	2
	no data	12.00%	No Data
Nijmegen Heyendaal	blind	5.39%	0
	windows (offices)	87.97%	1
	windows (shops, commercial service)	2.90%	2
	no data	3.73%	No Data

Figure 4-10 shows that majority of roads at both stations have level 1 (in orange color), but the general condition in central station is better than the other since there are more 'blind' roads' in area around Heyendaal station. The table 4.7 confirms the result that basically there is not much difference in the visual surveillance at these stations. It can be because most areas have residential and office buildings. The final figures in table 4-7 have been also rounded off to an integer because one street has two sides of buildings and the buildings might row up by their different types (see figure 4-11). The researcher took the principle of most on one side and average the two side numbers to be the final score for each street.

Even though some restaurants and shops with windows were assumed to have higher level of surveillance, some of these buildings are not open enough to reach a higher level of level 2 that could imply higher safety for pedestrian on the street (see figure 4-12). However, the central station area has more open-environment restaurants or shops than the Heyendaal area, which can be explained by its central characteristics.

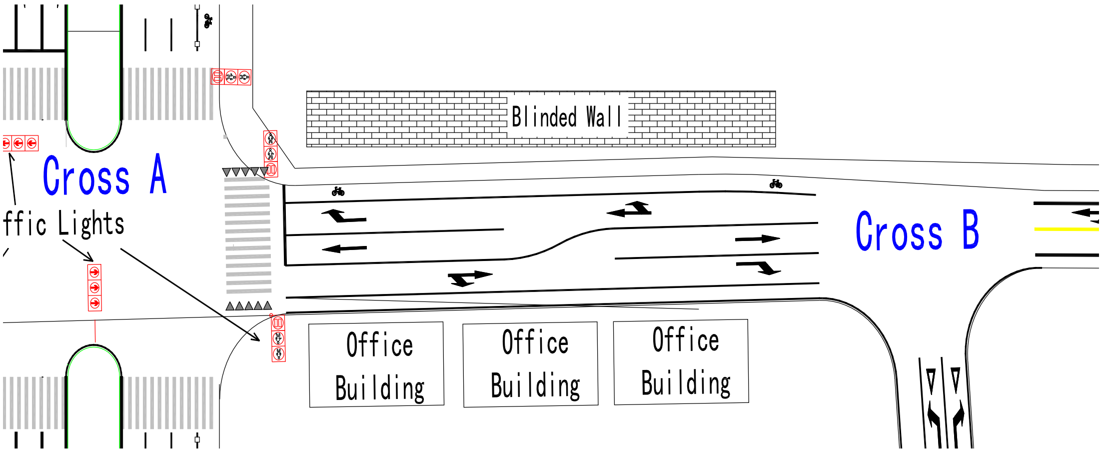
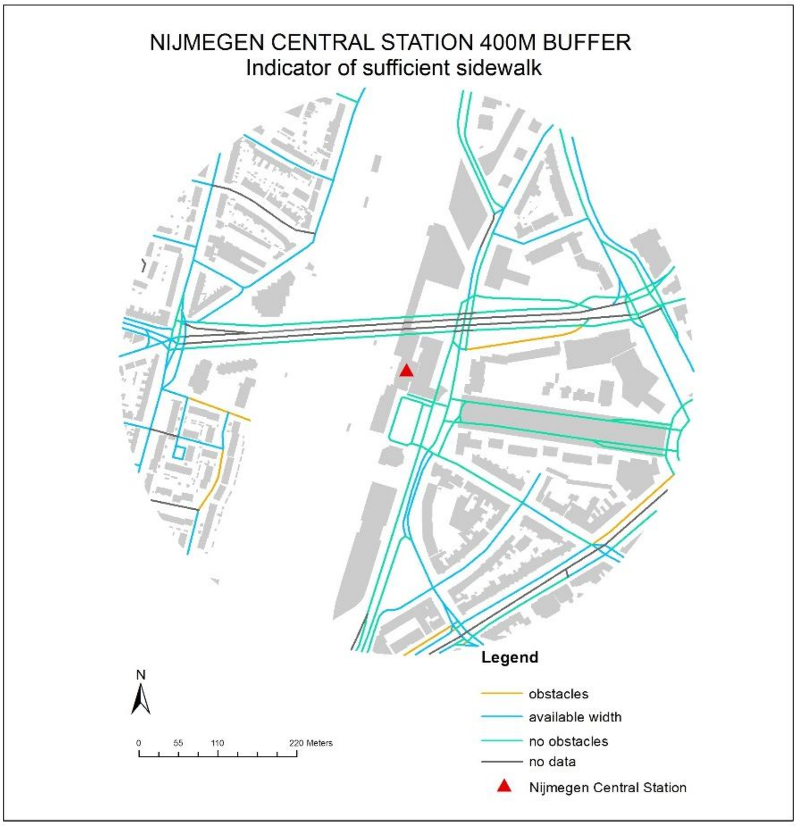


Figure 4-11: Scheme of mixed situation on one street in terms of visual surveillance

Figure 4-12: Restaurant not close to the walking path (left) and the open environment restaurant (right)

4.1.8 Urban design: Sufficient Sidewalks

The indicator of sufficient sidewalks examines the smoothness of a walking experience by studying the obstacles on the walking paths. It is difficult to measure the subjective sufficient space for walkers; however, the researcher used the obstacles that affect the behavior of walking to test the degree of sufficiency. The following maps give three situations of obstacles - obstacles force pedestrians to change routes or turn around, obstacles are present but still provide a smooth experience, no obstacles in the way.



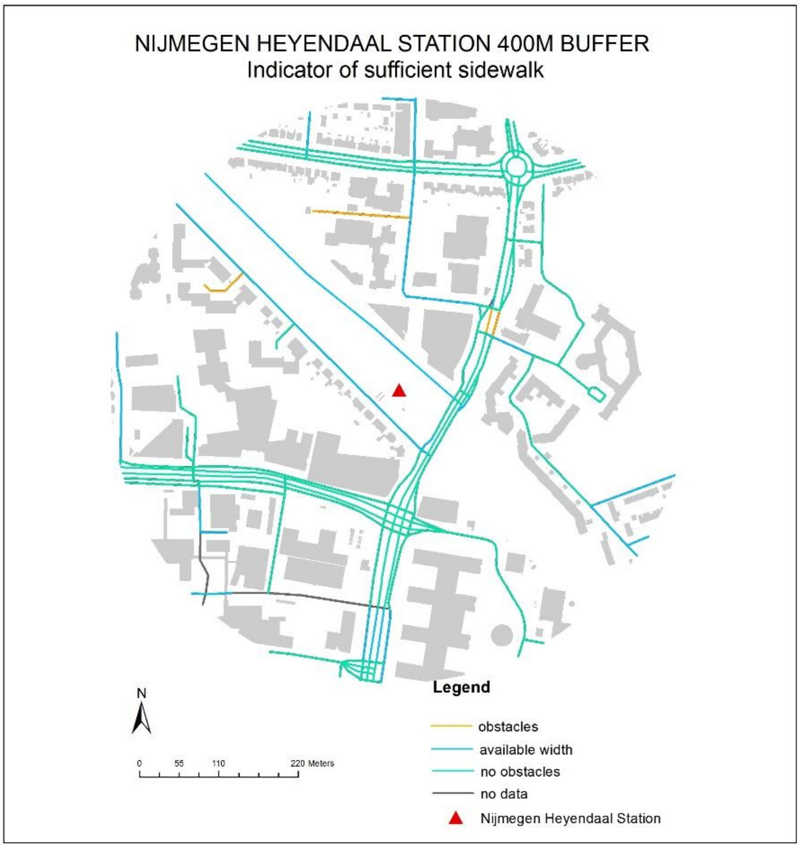


Figure 4-13: Indicator of sufficient sidewalk

Table 4-8: Level percentage of sufficient sidewalk

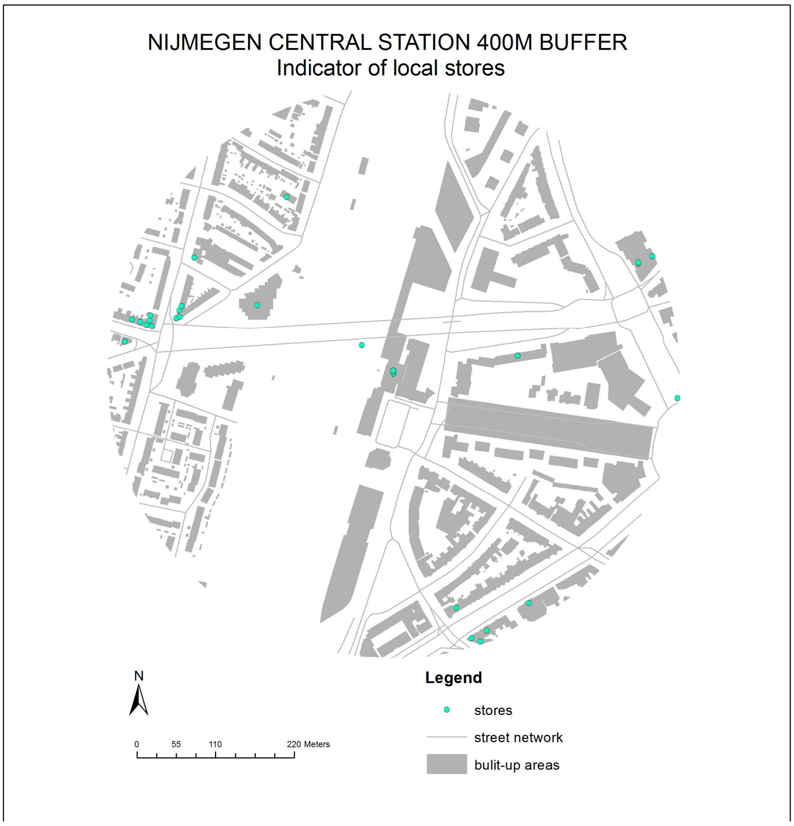
Sufficient Sidewalk	Description	Percentage	Level
Nijmegen Central	obstacles forcing people to leave the sidewalk	3.27%	0
	even obstacles exists but the available width is still sufficient	40.73%	1
	no obstacles	44.73%	2
	no data	11.64%	No Data
Nijmegen Heyendaal	obstacles forcing people to leave the sidewalk	1.66%	0
	even obstacles exists but the available width is still sufficient	15.77%	1
	no obstacles	78.84%	2
	no data	3.73%	No Data

It can be seen from the maps that Heyendaal station area has bigger size blocks and has less obstacles on the pedestrian paths as well. In figure 4-13 and table 4-8, we can see that almost 80% of the streets have no obstacles. For the central station, streets with reasonable obstacles and no obstacles have similar percentages, also totaling to about 80% of all roads.

The western part of the central station which is mainly residential in nature, has considerable quantity of long and narrow sidewalks with some private cars parking along them. This makes obstacles unavoidable. However, parts of streets near the roundabout or important commercial areas become wider and accommodate most of the pedestrians and provide wider vision as well.

4.1.9 Urban design: Local Stores

The existence of the stores around the train station manifest the major focus in TOD concept that mixed land use (diversity) near the major centers could attract the transit mode choices and encourage more physical activities within a certain area. The following maps shows the location of stores and how they are distributed in areas around the two station.



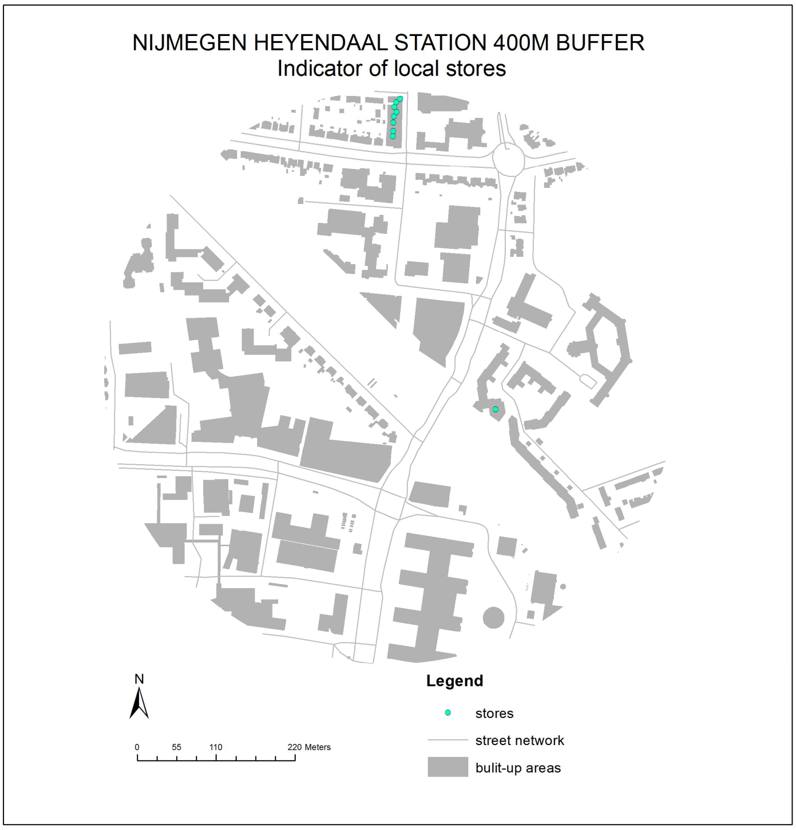


Figure 4-14: indicator of local stores

Table 4-9: Level of local stores

Local stores	Counts	Level
Nijmegen Central	37	1
Nijmegen Heyendaal	9	1

The secondary data provides the location of the built-up areas, as well as the usage of each building by points in ArcGIS. For example, there are more than 2000 points within the buffer around central station, 37 of which used as 'stores' (figure 4-14). Thus the percentage is excluded for its showing pointless. In the table 4-9, the two stations are both assigned level 1 due to number of stores in the area. Even though the number of stores in central station is almost four times than in Heyendaal, within the defined area of 400 meters, the difference tends to be insignificant as they have the same level.

4.1.10 Urban design: Path condition

The indicator of path condition examines the existing paving materials that provide a smooth pedestrian surface to walk on. As there are quite important street segments around the train station and with a typical well developed transportation environment, walking paths with no pavement are scarcely found. Therefore, this research assumes that all streets satisfy the condition and are assigned the level 1 in table 4-10. The figure 4-15 shows the typical residential pedestrian condition, as well as the area close to the other uses.

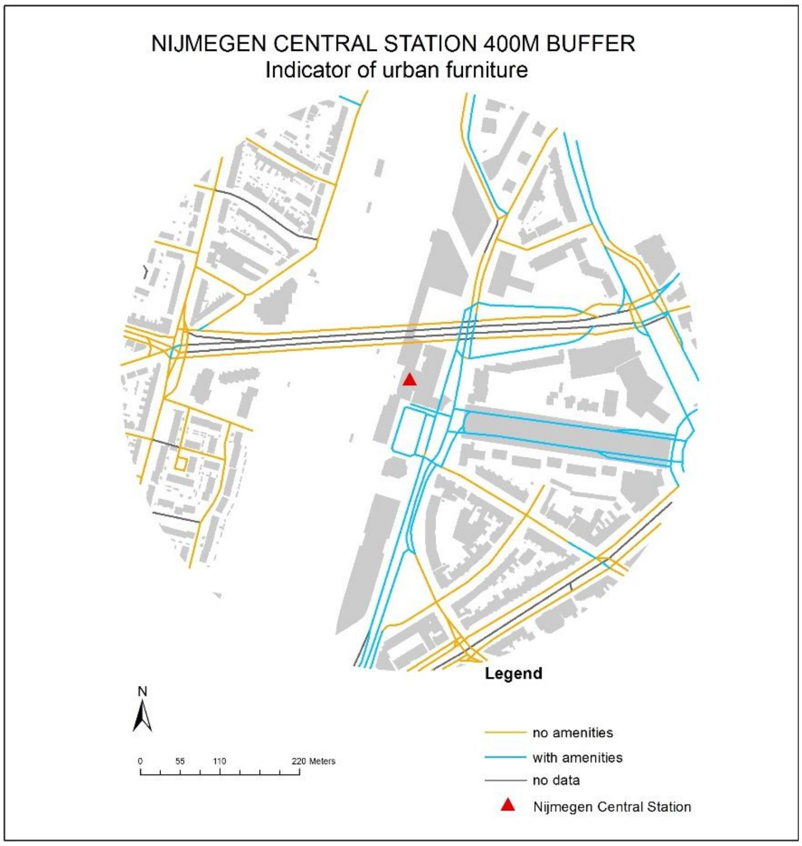
Table 4-10: Level percentage of path condition

Path Condition	Description	Percentage	Level
Nijmegen Central	with paving materials and easy to walk	100.00%	1
Nijmegen Heyendaal	with paving materials and easy to walk	100.00%	1

Figure 4-15: Typical walking path condition in both areas

4.1.11 Urban design: Urban Furniture

The urban furniture refers to the furniture on street in urban cities that provide not only convenience for the pedestrians in need (for example, benches), but also refer to the facilities that are provided for people's enjoyment and comfort. Therefore, the word 'amenities' can be used for measuring the level of urban furniture in the following maps. However, in most of the context, the pragmatism has been widely put forward and thus the presence of the furniture that meets the basic needs of convenience when walking in this case is the only measurement standard.



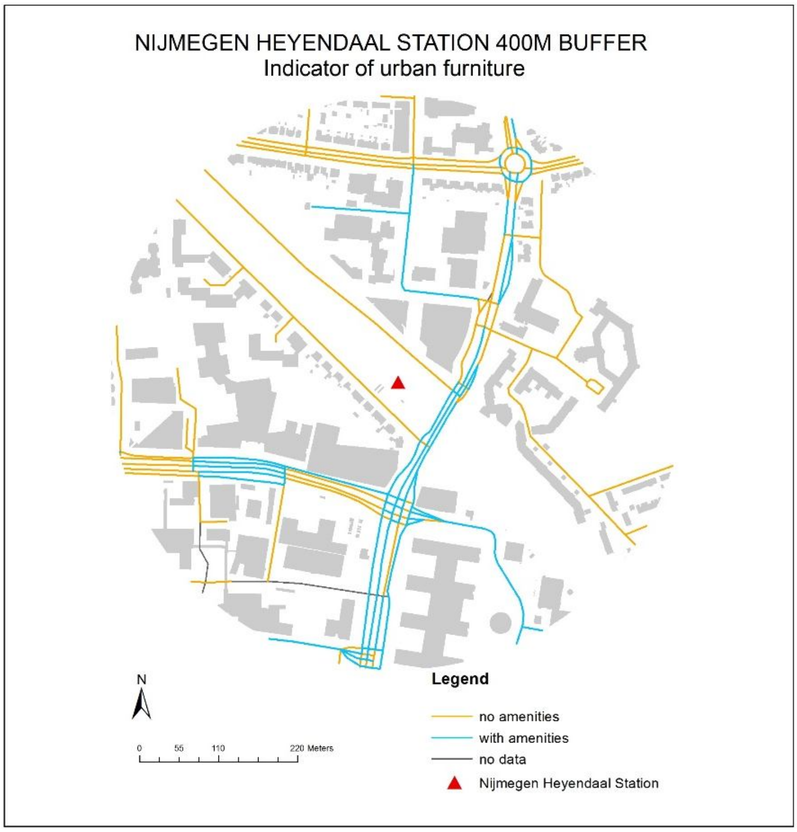


Figure 4-16: Indicator of urban furniture

Table 4-11: Level percentage of urban furniture

Urban Furniture	Description	Percentage	Level
Nijmegen Central	no amenities	56.00%	0
	with amenities	32.73%	1
	no data	12.00%	No Data
Nijmegen Heyendaal	no amenities	50.62%	0
	with amenities	45.64%	1
	no data	3.73%	No Data

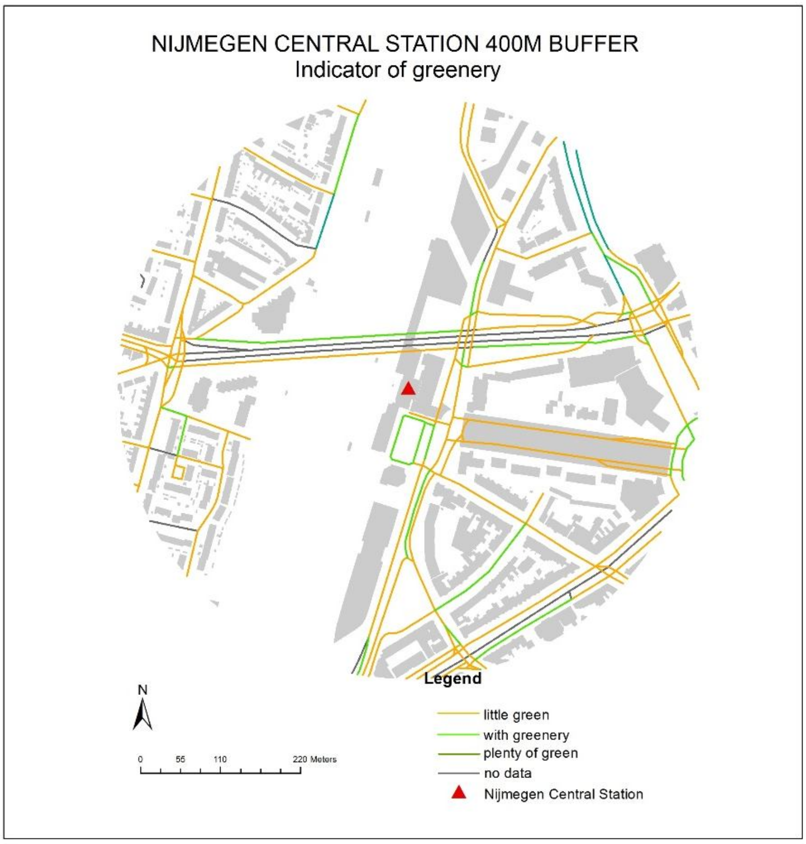
The urban furniture on street includes trash bins, benches, ATMs etc. From the maps in figure 4-16, about half-and-half situation of with and without furniture is spread within both the station areas. Table 4-11 explains the similar numbers for each station while the Heyendaal area seems to possess more furniture. Locations near the roundabout or big intersections, where there are higher pedestrian flows, shows more frequent appearance of furniture. The pictures in figure 4-17 are the examples of urban furniture found along the streets.

Figure 4-17: ABN Bank along the walking path at Nijmegen Central (left) and trash bins on the crossing path at Nijmegen Heyendaal

4.1.12 Urban design: Greenery

The indicator of greenery is a proxy for measuring the attractiveness of the streets. The absence of level 0 means 'no green' has been found non-existent. The examination of the greenery indicator was based on the secondary data offered by Fietsersbond (2016). Descriptions included two extreme conditions - plenty of green that resembles a village environment such as city parks and walks with lush front gardens and trees in urban areas, and little green that runs through areas with little green such as only trees standing along the road or only a grass strip (figure 4-18). Fieldwork was also done by the researcher to assess levels of green.

Figure 4-18: Condition of plenty of green (left) and condition of little greenery (right)



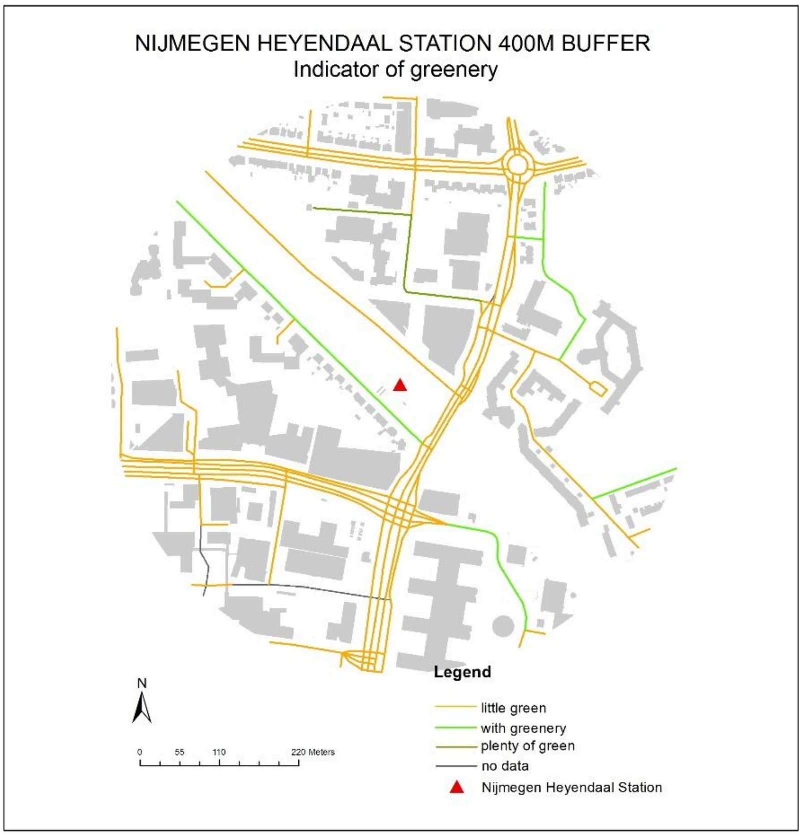


Figure 4-19: Indicator of greenery

Table 4-12: Level percentage of greenery

Greenery	Description	Percentage	Level
Nijmegen Central	little greenery	73.09%	1
	with greenery	13.45%	2
	plenty of green	1.45%	3
	no data	12.00%	No Data
Nijmegen Heyendaal	little greenery	92.12%	1
	with greenery	3.32%	2
	plenty of green	0.83%	3
	no data	3.73%	No Data

The resulting maps (figure 4-19) reveal mostly orange color for little green along most of the walking paths around both stations. Table 4-12 shows that area around central station has less proportion of 'little greenery' (level 1) as compared to the Heyendaal area. The area around central station also has more 'plenty of green' areas such as the "kronrnburgersingel" street with a naturally park alongside. In general, most of the green landscape in the area of Heyendaal station, seems to be artificial.

4.2 Calculation of the Walkability Index

After the measurement of all indicators for all the walking paths within the two areas, the next step was to normalize their scores (ranging from 0 to 4) into scores between 0 and 1. The normalization is necessary because it helps to establish relationships between tables and their figures according to specific rules. There are 12 indicators involved in this research and not every indicator has the same number of levels to assign, which means that the difference in the highest level among indicators could create inconsistency in the whole system of the walkability index. It also helps to obtain one final score of the walkability index for the two stations and make the results comparable and lead to a significant discussion towards the final results.

Unlike other criteria that assign each road a score of level, the criteria of accessibility with its two indicators are leveled by the percentages within the two station buffers. Thus, the researcher assigned all the streets in the buffer the same level as the overall percentage-based level. In other words, each street segment has the same level of indicators of IPCA and intersection density.

The renewed scores are calculated by the formula as follows, in which the "value" is the level that indicators get. The lowest value is 0 and the highest value can be up to 4 (see table 3-2). The figure 4-20 gives an example fragment of how the scores change after the normalization steps.

Score = (value-lowest value) / (highest value-lowest value)

OBJECTID	IPCA	intersection density	speed	segregation	crossing facilities
1	1	2	1	2	1
2	1	2	1	2	3
3	1	2	1	2	3
4	1	2	1	3	3
5	1	2	1	3	3
6	No Data	No Data	No Data	No Data	No Data

OBJECTID	IPCA	intersection density	speed	segregation	crossing facilities
1	0.50	1.00	1.00	0.67	0.25
2	0.50	1.00	1.00	0.67	0.75
3	0.50	1.00	1.00	0.67	0.75
4	0.50	1.00	1.00	1.00	0.75
5	0.50	1.00	1.00	1.00	0.75
6	no data	no data	no data	no data	no data

Figure 4-20: New scores after normalization steps

The final scores for the indicators are showed in the upper table in figure 4-21. These numbers are the sum of the scores assigned to all walkable street segments within the 400m buffer around the two station. Moreover, the numbers are given in up to two decimal points, to keep them accurate when the scores are divided by the total number of the streets and show their relative importance in the radar charts in figure 4-22. As mentioned before, all the indicators should be weighted for a base model of walkability index. Another normalization step then is processed to have comparable and relational results between the two sets of scores. The equation is presented as follows, in which the "sum value" is the total after the first normalization step, and the table downside in figure 4-21 shows the updated scores.

*Score = (sum value/amount of streets) *100*

	IPCA	intersection density	speed	segregation	crossing facilities	lighting	visual surveillance	sufficient sidewalks	stores	pavement	furniture	greenery	**Corrected amount of streets**
Nijmegen Central	121.50	243.00	174.00	175.33	133.50	237.00	123.50	179.00	243.00	243.00	90.00	96.00	**243**
Nijmegen Heyendaal	116.00	232.00	126.00	152.67	110.13	171.50	102.25	209.00	232.00	232.00	110.00	81.33	**232**

	IPCA	intersection density	speed	segregation	crossing facilities	lighting	visual surveillance	sufficient sidewalks	stores	pavement	furniture	greenery	**Corrected amount of streets**
Nijmegen Central	50.0	100.0	71.6	72.2	54.9	97.5	50.8	73.7	100.0	100.0	37.0	39.5	**243**
Nijmegen Heyendaal	50.0	100.0	54.3	65.8	47.5	73.9	44.1	90.1	100.0	100.0	47.4	35.1	**232**

Figure 4-21: Final scores for indicators at two stations

With the defined weights (see Chapter 3.4), the final score of the walkability index can be obtained, scores ranging from 0 to 100. The walkability calculation expression is:

***Walkability* =**

*0.1*IPCA + 0.1* Impedance based Intersection density + 0.0667 * Walking affected by traffic + 0.0667 * Segregation of the paths + 0.0667 * Crossing facilities + 0.1* Street lightning + 0.1 * Visual surveillance + 0.05 * Sufficient sidewalk + 0.05 * Access to local stores + 0.05 * Path condition + 0.05 * Amenities + 0.2 * Greenery*

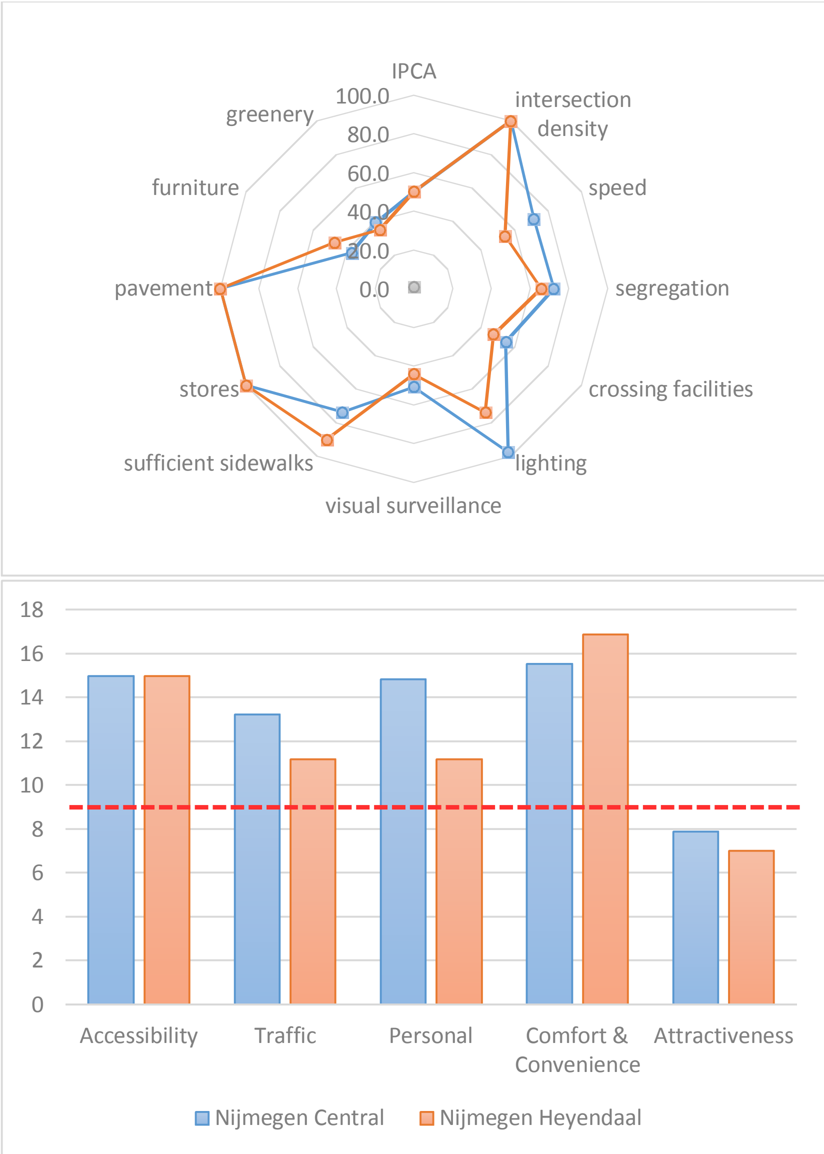
The table 4-13 and table 4-14 demonstrate the proportion in the last column for the each criteria for the two station areas. The radar chart in figure 4-22 shows the relative importance of each indicator, and the bar chart shows the final proportion for criteria.

Table 4-13: A base model in Nijmegen Central

Criteria	*Indicators*	*SCORE*	*Weight*	*Weight*Score*	*Weight* Score*
Accessibility	IPCA	50	0.1	5.00	15.0
	intersection density	100	0.1	10.00	
Traffic	walking affected by traffic	71.6	0.0667	4.78	13.3
	segregation of the paths	72.15	0.0667	4.81	
	crossing facilities	54.94	0.0667	3.66	
Personal	street lighting	97.53	0.1	9.75	14.8
	visual surveillance	50.82	0.1	5.08	
Comfort & Convenience	sufficient sidewalk	73.66	0.05	3.68	15.5
	local stores	100	0.05	5.00	
	pavement	100	0.05	5.00	
	urban furniture	37.04	0.05	1.85	
Attractiveness	greenery	39.51	0.2	7.90	7.9
TOTAL		**847.25**	**1,0**	**66.52**	**66.5**

Table 4-14: A base model in Nijmegen Heyendaal

Criteria	Indicators	SCORE	Weight	Weight*Score	Weight* Score
Accessibility	IPCA	50	0.1	5.00	15.0
	intersection density	100	0.1	10.00	
Traffic	walking affected by traffic	54.31	0.0667	3.62	11.2
	segregation of the paths	65.8	0.0667	4.39	
	crossing facilities	47.47	0.0667	3.17	
Personal	street lighting	73.92	0.1	7.39	11.8
	visual surveillance	44.07	0.1	4.41	
Comfort & Convenience	sufficient sidewalk	90.09	0.05	4.50	16.9
	local stores	100	0.05	5.00	
	pavement	100	0.05	5.00	
	urban furniture	47.41	0.05	2.37	
Attractiveness	greenery	35.06	0.2	7.01	7.0
TOTAL		808.13	1,0	61.86	61.9



**The red dotted line represents the boundary between a positive result and a negative one*

Figure 4-22: Walkability assessment in two station areas

Final walkability index score for Nijmegen Central Station is **66.5** and **61.9** for Nijmegen Heyendaal Station.

4.3 Conclusions

The scoring of the 12 walkability indicators and their concluded results gives the evidence of proportion of each level assigned to each street segment. The visualization through GIS maps for indicators help in further discussion of each feature within one or among station areas.

A score of 60 can be recognized as an above average performance of walkability yet not excellent. The Nijmegen Central Station is observed as the most important transportation hub in the city and has a walkability index score of 66.5. The comparison is also possible with another major station of Nijmegen Heyendaal with a walkability result of 61.9. These two numbers could both be accepted as reasonable scores and with a little difference given their sole values. With their similar radar chats, it appears that the two areas have similar characteristics in their built environment.

It is also possible to assess the walkability in catchment by indicators and by their criteria. We can expect that being a central station naturally resulted in generally higher scores as compared to other less important stations. However, fluctuations in the charts above provide more than the information about final walkability scores and help to understand the advantage and disadvantage among indicators and criteria. As can be seen from the radar graph, in general, the indicators of intersection density, lighting, local stores and path condition have the best scores. Indicators such as sufficient sidewalks and segregation score more than IPCA, urban furniture and greenery. The bar chart conveys the general pattern that criteria of comfort & convenience has the most positive score and the only negative score was for attractiveness. From a comparison perspective, despite the similar patterns in both charts for the two stations, the Nijmegen Central does better in most of indicators except for sufficient sidewalks and urban furniture.

In practical terms, it is explainable that within the Dutch context this situation would be expected, because the transportation systems are already mature enough to put more emphasis on the other design factors of comfort and convenience, other than the basic issues of accessibility and safety. The results reveal the lack of development to create attractiveness around transit nodes, and this is exactly the opportunity and breakthrough point that can gain the global attention in terms of TOD in most of well-developed European countries. However, in this study, only green infrastructure has been considered for the criteria of attractiveness. In order to obtain a more profound result, a more in depth look into what is considered as attractive in the built environment around and leading to the stations should also be added to an assessment. Meanwhile, the city authorities could explore new approaches to “greening the city” to add a more attractive urban environment in which pedestrians like to walk. For example green walls, green roofs, plants hanging from the lampposts, etc.

5 Final discussion and conclusions

In this final chapter, a discussion of the main findings of this thesis are presented, including potential contribution to the research field, reflect on the difficulties and opportunities regarding the limitations of this study, and propose further follow-ups from this study. To reiterate, the main goal of this thesis is to develop an index that measures walkability indicators to improve the assessment of TOD transit nodes.

5.1 On the importance of walkability for TOD research

Two major and important stations are selected and assessed to the extent of 400 meters buffer limit. They were selected as they both are understood to have good quality transport systems and meet the condition of developing a transit-oriented neighborhood. Thus they are suitable for assessing the TOD by examining the level of walkability within these areas. The research problem lies in the often-ignored while important component of TOD, which is walkability, and its index, where the researcher claims that including design features in the built environment is a must. Walkability has been singled out as a key factor in best urban design practice since it is a significant contributor to a quality urban environment. That is to say, walkability itself can be explained by an urban design problem. In a TOD sense, current research has tried to include walkability research to assess if it meets the basic needs of walking. A long-term outlook is that walkability plays an important role in attracting young and creative groups who value access to public transit with a safe and comfortable environment. TOD and walkability have a common goal of transforming rapid urbanization and congestions into a connected society with sustainable development. However, walkability in TOD research tends to be studied only from accessibility point of view and the design concerns are not properly studied. I aimed at combining the other dimension of TOD walkability with a purpose of considering design features in the built environment, other than the merely fundamental factor of accessibility in which most research gaps with other factors exist. Through an extensive literature review from different fields, the researcher reached a greater understanding of the walkability concept and its different aspects in which the built environment influences walking. This research studies walkability within the geographical scale based on a typical TOD catchment area around a transit node.

A representative list of walkability indicators including three dimensions of TOD - fundamental, safety and urban design, was developed in this thesis, consisting of 5 criteria and 12 walkability indicators that are able to assess the performance of walkability in a TOD context. A proposed base model was developed to assign equal weights to criteria and distribute the weights down to their indicators. Here, an alternative way is to assign equal weights to each indicator. Although, it was ensured that the fundamental importance of accessibility is kept, equal importance of urban design was also explored in which a lot of determinants exist. The dimension of safety is also included since walkability in built environment demands basic elements like calm traffic environment and personal security at the same time. Therefore, the three dimensions in this developed walkability index reached a more balanced theoretical structure by explaining the concept of TOD walkability in it.

The accessibility as a TOD fundamental was examined by two indicators – PCA within 5 minutes walking distance and intersection density that corresponds closely to the principle of smaller block size equaling a more walkable neighborhood. The intersection density has been proved in American society to have the most important effect on walking, and normally uses free databases that have broad geographic coverage. Thus it is a favorable and better measurement to compute intersection density through the embedded street network information. The same favored reason is also true with the measurement of PCA. The contribution to this dimension in this thesis is that the research draws advantage of smaller catchment areas, based on the TOD scale, and makes more accurate results in terms of both indicators of accessibility by identifying all the inaccessible areas such as dead ends and tunnels in the street layout and exclude them.

All the indicators of safety and urban design are exhaustive and non-redundant products selected by a screening process from the literature. These two criteria have 10 indicators, constituting fifth-sixth parts of the whole indicator list. The indicator list tries to include as many aspects as possible. The measurement of performance levels in which an ordinal set of impacts is plays a great role and is effective in describing built environment without ambiguity. This is a useful measurement that fills the value scales with subjective descriptions, which are often found difficulty to measure. This process of transforming a traditional transportation issue into a broader issue of built environment that affects walking is actually the main objective of this study. This study developed a tool that would enable the walkability assessment, but at the same time within a TOD research scale. This index expands on the existing studies of American walkability by influential academics such as Reid Ewing and Robert Cervero. The European context offers the chance to review the TOD concept and add new focuses.

The application of the base model reported the final walkability scores of 66.5 and 61.9 (max 100) in two important areas in Nijmegen. The results confirm the general impression of this historical city coupled with a small but compact center dedicated to create a walkable environment throughout the area. However, it is noteworthy that a higher score of walkability in an area does not mean more people would choose to walk here or live here. It means a set of walkable requirements are met to some extent and within the scope of study it is believed to meet more standards than the others. The obtained output in this thesis and their visualized details of each walkability indicator opens a channel to invite suggestions and guidance based on closer looks and deeper understanding between the areas. Being nearby areas in one city, these two areas proved that neighborhoods are not isolated entities and share characteristics of the whole. Thus, by applying the model to other urban areas could draw more comprehensive conclusions.

5.2 Limitations

Even though a refining process of choosing indicators has been conducted in this thesis, it is based on contributions from representative studies in history that mainly relate to TOD and walkability topics. The research relied heavily on the wealth of experience from all these authors. But in this way of searching broadly, combing opinions and then narrowing down to develop a new walkability index in the context of TOD, the supportive scientific evidence of how to choose the indicators is limited.

The level descriptions with their discrete data among worst and best performances have limitations too. These data are ordinal and interval and obtained from the similar form of Likert scales that the parametric statistics are barely in use. Discrete scales are filled with descriptions that often end up in a sense of qualitative judgement rather than statistical significance. For example, there is no evidence that shows how to guarantee the true distance between the thresholds and how the analysis gives objective definitions that reflect on the numbers of level/ threshold. However, this is not to say the results will differ a lot due to the methods being used, it is the lack of the evidence that prove the ‘robustness’ towards the results by using different methods, in other words, to prove little chance of erroneous conclusions if using this measurement whereas not using the others.

Other limitations are linked to how values were calculated. Such issues happen when, for example, the less intervals defining an indicator level may cause a more generalized output in the results. Also for some mixed situations (i.e. indicator of visual surveillance and crossing facilities) averaging the scores for one unit of segment may have caused some inaccuracy in the end among the other exact numbers. Another limitation is a possible incoherence in the final index as the criteria of accessibility used percentages to score the same for all the streets, which is different from the other indicators where each segment has their own score.

The data resources were also limited and only accessibility could be included. Information such as age groups, employment, travel behavior and patterns might be crucial in contributing to more purposeful indicators with more clarity, on how walking behavior and built environment around TOD nodes interact with each other.

At last but not least is the time and cost associated to the research. A questionnaire that is ready to help the applicability of the walkability index by weighting in a real situation is left for further research. The ranking weight steps include group sampling, interviewing them and then analyzing the results of the interviews. These are time consuming and costly. Moreover, the study area within 5 minutes of walking distance has its advantages in the name of TOD research, but future research should take into account a wider range of 10 minutes and 15 minutes buffer (scale mix), since the comparison would lead a more comprehensive conclusion and productive discussion. Ideally, other nodes in the TOD area should also be assessed to provide more information about walkability performance, and about how useful this index is in the assessment of, for example, suburban nodes or areas with a low TOD level.

5.3 Future research

According to the research result, interventions in the study area should put effort on how to improve the quantity and quality of urban furniture and greenery, which perform the lowest when compared to the other indicators. Visual surveillance improvements are difficult to realize because they have to involve the whole urban form/land use change and construction. Thus, aspects that are not firmly restricted by the existing conditions have the most potential for improvement. From this point of view, the awareness of developing the aesthetic aspects in urban design field should be raised. For practitioners in a European context, I assume that it is a natural step since a mature transport system has already been well developed. It also makes sense if we take a look at the criteria chart that the attractiveness performs the lowest among others. Urban furniture has connection to the criteria of attractiveness when it meets a certain level. In fact, all the comfort and convenience indicators can reach a level in terms of attractiveness. This is also the reason for the difficulties in defining the indicator of attractiveness. Further improvements can develop the topic of transformation from the functional units to aesthetic design, giving the appropriate definition to the ‘attractiveness’ and its determinants under different context, before which the particular techniques can be suggested to form suitable intervention guidelines.

For the method of impact levels, further improvements can be done by collecting more information and samples to get a better understanding of how to identify the quality of performance (from the best down to the worst) and better calibrate the intervals among levels. Other than the perception from normal group of people, experts in the field or from the relevant cross-section and policymakers are suggested to be involved in order to obtain an improved set of indicators.

Other improvements can be in validation of the model. Because the model was developed based on the Dutch context, as well as the context of TOD in European countries, the topic is actually quite new. Therefore, it is important to put the model into practice by using questionnaires, surveys and others to see how the local weighting would affect the results compared to the base model that is being used. Sometimes, a good score of walkability index overall, covers the facts that the lower scores are compensated by the much higher scores. Thus, different contexts and how their citizens weigh the indicators would have a great influence on the final results. The perception matters and the overall walkability are relative. Thus, a more comprehensive observation should be developed in the future research.

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7 ANNEX

ANNEX A Checklist for fieldwork (Template Version)

Remark: *a** and *b** refer to the percentage-based indicators that in the end will assign all the streets the same level regarding the result of percentage.

Fieldwork Checklist

Indicators / Sidewalk ID	a*	b*	c	d	e	f	g	h	i	j	k	l
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
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26												
27												
28												
29												

Figure 7-1: Checklist sample for fieldwork

ANNEX B Maps for fieldwork

Remark: the roads which share the same color usually share the similar characteristics that can help the researcher during the fieldwork.

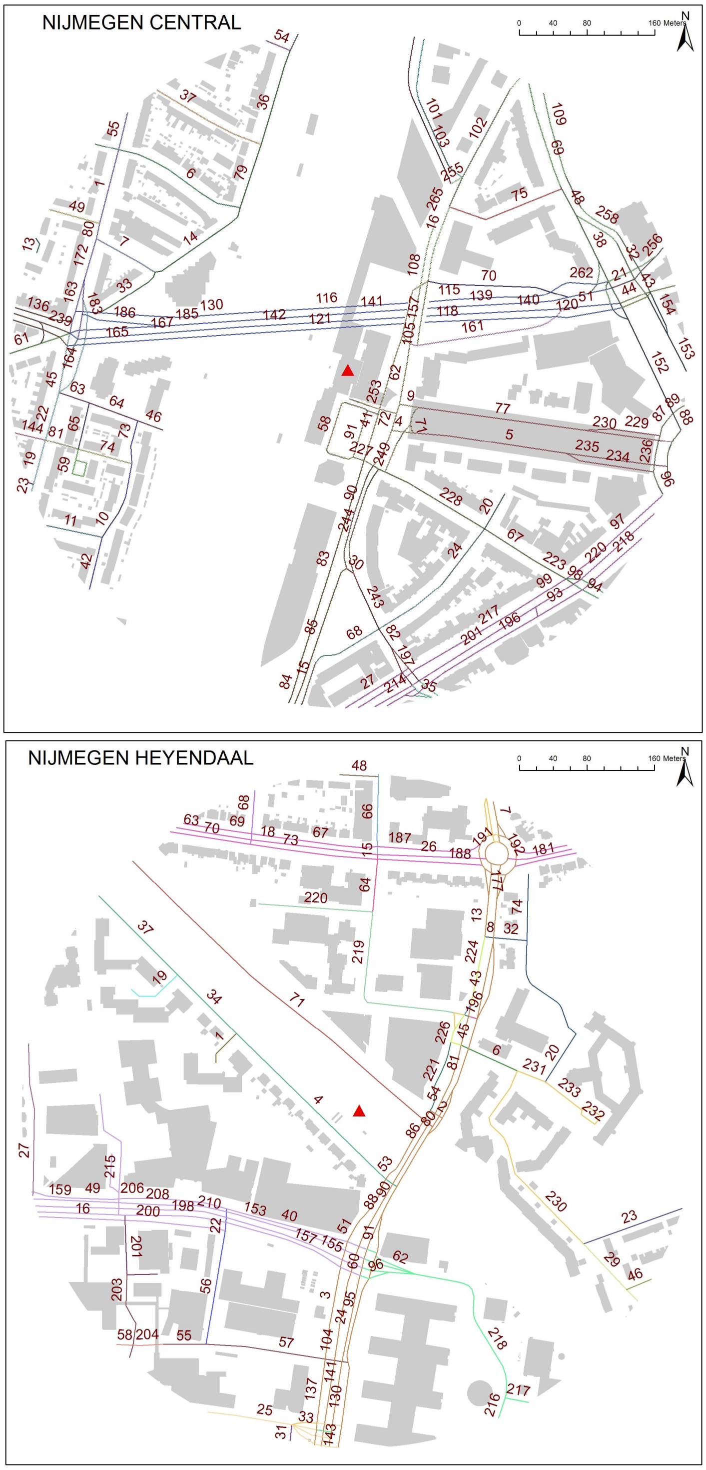

Figure 7-2: Map used for fieldwork