Developing a bikeability index to enable the assessment of Transit-Oriented Development (TOD) nodes.

Case Study in Arnhem-Nijmegen Region, Netherlands

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March, 2017

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ABSTRACT

Transit-oriented development (TOD) is one of the approaches adopted in urban planning to stimulate sustainable urban transport development. TOD encourages people to use non-motorized modes on their travel to transit nodes. Shifts from car use to cycling or walking decrease traffic congestion, road and parking facility costs and environmental impacts, and improve public health (Cervero & Kockelman, 1997).

The encouragement of cycling must be supported by appropriate infrastructure and must take place in an environment that is conducive to cycling. It should make cycling not just safe, but also easy, attractive and comfortable. Investments in cycling infrastructure around transit nodes aim to promote the bicycle as a feeder mode to transit. When cycling infrastructure around transit nodes is adequate, the so-called TOD-ness of the area will increase because transit will be more accessible by bicycle (Singh, 2015). In the Netherlands, the concept of TOD is most relevant in the context of the national railway system that links all major and secondary cities. Cycling is by far the most important access mode to this system (Kager, Bertolini, & Brömmelstroet, 2016).

The assessment of TOD regarding cycling infrastructure is commonly looked at in combination with pedestrian networks, measured by the length of cycling/ pedestrian networks, and intersection density. However, we argue that these are different in nature and scale. Exploring specific indicators would then contribute to a more thorough evaluation of the extent to which a TOD environment is bikeable (or walkable). This study therefore develops a bikeability index that specifically enables the assessment of TOD-ness around transit nodes. Literature review on methods to measure bikeability supported the selection of indicators that are appropriate in a TOD context. The indicators are based on the five principles of cycling infrastructure network planning (coherence, directness, safety, attractiveness, and comfort) (Bach, 2006). In addition, because this study explores the bicycle as the feeder mode to transit, the quality and features of bicycle parking at the train stations were also used as an indicator to measure the quality of infra provision (Van der Spek & Scheltema, 2015).

A bikeability index is demonstrated for 21 train stations in the Arnhem-Nijmegen region, in the Netherlands. This is a region that suffers from increasing congestion and integrated spatial and transport planning focusses on strengthening the role of TOD. Spatial data of cycling infrastructure and station environments was used to measure the bikeability indicators, in relation to three spatial scales: 800 meters, 1600 meters and 2400 meters circular area. The combined scores of the indicators result in bikeability indices for each of the stations. No significant differences on the overall bikeability index were found. However, there are some significant differences on the criteria score.

Two typologies were used to analyse the 21 stations, leading to the analysis of differences on bikeability of urban and suburban areas. It was found that urban stations tend to score lower on bikeability than suburban stations. The bikeability index developed in this study was based on a more extensive list of indicators, and serve a different purpose than previous realted literature (Singh, 2015). The comparison of results would allow understanding whether extending the list of indicators to measure bikeability would result in major or minor differences when compared to a more concise indicator.

The bikeability index here developed provides a more detailed view on which factors affect cycling behaviour when the bicycle functions as a feeder mode to transit, which can only be captured with a more extensive list of indicators. This is especially relevant for policy makers when the interest is on strengthening the bikeability in urban or suburban areas.

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1. INTRODUCTION

1.1. Background and justification

Transit-oriented development (TOD) is one of the approaches adopted in urban planning to address problems caused by rapid urbanization, such as congestion. Increasing the ridership of public transport and reducing the use of private motorized vehicles by changing the built environment is one of researched subject in urban planning. The most common indicators to measure the TOD potential of an area are the so-called"3Ds," of the Built Environment, which are density, diversity, and design (Cervero & Kockelman, 1997)). These were followed by two more indicators destination accessibility and distance to transit (Ewing & Cervero, 2001; Ewing et al., 2009). The 5Ds of the built environment indicate that high-density areas with diverse land use, pedestrian/bicycle-oriented design, with high destination accessibility and low distance to transit are the built environment factors that can reduce car use and encourage the usage of public transport.

TOD is not only about physical factors, but also about the relationship between individuals and their communities. The aim is to create environments that encourage people to drive less and ride public transit more (Cervero, 2014). Results of a study by Nasri and Zhang (2014) indicate that compared to the residents of the non-TOD areas, people living in TOD areas tend to drive less, reducing their motorized vehicle travel (VMT).

TOD also encourages people to use non-motorized modes on their travel to transit nodes. Shifts from driving to cycling or walking can decrease traffic congestion, road, and parking facility costs and environmental impacts and improve public health (Ministry of Transport Public Works and Water Management & Fietsberaad, 2009). Street design that supports walking and cycling are deemed as one of the factors that will improve the "TOD-ness", a term first developed by Evans and Pratt (2007, p.17) meaning "…potential device for considering the degree to which a particular project is intrinsically oriented towards transit". The design of urban space that makes an area walkable and cyclable is thus an important influence for TOD design and planning.

This research is focussed on bikeability in a TOD environment. Lowry et al. (2012) defined bikeability as "an assessment of an entire bikeway-network in terms of the ability and perceived comfort and convenience to access important destinations" (p. 43). On this research, a new bikeability definition will be formulated later on based on the literature review related to bikeability in a TOD environment. The encouragement of cycling must be supported by appropriate infrastructure. The design of infrastructure should make cycling not just safe, but also easy and comfortable for everybody (Marques et al., 2015). A study by Amir et al. (2016) found a significant association between the index of bicycle infrastructure accessibility and bicycle mode choice - an increase of 10% in the accessibility index results in a 3.7% increase in the ridership - and also the important benefits of bicycle infrastructure to reduce commuting automobile usage and greenhouse gas (GHG) emissions.

The aim of investments in cycling infrastructure around transit nodes is to promote the bicycle as a feeder mode to transit. When the cycling infrastructure surrounding transit nodes is adequate, the TOD-ness of the area tends to increase because transit will be accessible also by bicycle. Local government as well as investors should be assured that their investment in TOD infrastructure is efficient and effective. This is one of the reasons why there is a need to better understand how to measure bikeability in a TOD environment. The high level of bikeability will assure governments that their infrastructure investment is worthy. On the other hand, it is expected that local government would improve the cycling infrastructure on the less cyclable areas around transit nodes.

1.2. Research problem

The TOD Index developed by Singh (2015) for the region Arnhem-Nijmegen (Netherlands) included many criteria that allowed measuring the TOD-ness of an area. One of the criteria related to the assessment of urban design around TOD nodes was captured through the combined analysis of walkability and bikeability. Indicators of this combined criterion were measured through: mixed-ness of residential land use with other land uses, the total length of walkable/cyclable paths, intersection density and impedance pedestrian catchment area (IPCA). However, this research claims that walkability and cyclability are different in nature and should be analyzed and measured by a different set of indicators and that the list of indicators will be potentially much more extensive. The present research has its focus on bikeability around transit nodes, applied to the same Dutch case study, whereas another MSc researcher at ITC (Ms. Yang Xu) will focus on walkability.

In the revised literature, bikeability is commonly measured regarding safety and compatibility aspects. For instance, The United States Department of Transportation (2007), (2008) has developed two indices to measure bikeability. 1) Pedestrian and Bicycle Intersection Safety Indices (Ped ISI and Bike ISI): it proactively prioritize pedestrian crossings and bicyclist approaches with respect to safety; 2) Bicycle Compatibility Index (BCI), used by bicycle coordinators, transportation planners, traffic engineers, and others to evaluate the capability of specific roadways to accommodate both motorists and bicyclists. The BCI model provides practitioners the capability to assess their roadways on compatibility for shared-use operations by motorists and bicyclists and to plan for and design roadways that are bicycle compatible.

However, in a TOD environment, there is a need to measure bikeability surrounding transit nodes, which combine the safety, compatibility and also a street design element. Regarding TOD, the street design should encourage people to use the bicycle as a feeder mode to public transport, such as a bus stop or a train station. Therefore, this thesis proposes to develop a new bikeability index for TOD transit nodes.

1.3. Research objectives

The main objective of this research is to **develop a bikeability index to enable the assessment of TOD transit nodes, in order to improve the TOD-ness of an area**. The sub-objectives include:

1. To review methods in literature that measure bikeability
2. To design a bikeability index that is appropriate in a TOD context
3. To demonstrate the applicability of the bikeability index in a case study
4. To analyze differences in bikeability index values in a case study
5. To analyze the differences of bikeability index value and indicators score in different spatial scales of TOD area

1.4. Research questions

Table 1. The research questions

Research sub-objectives	Related research question(s)
1. To review methods in literature that measure bikeability	1.1. What is understood of bikeability?
2. To design a bikeability index that is appropriate in a TOD context	2.1. What are the indicators on existing indices that relevant for TOD development?
3. To demonstrate the applicability of the bikeability index in a case study	3.1. How to apply the new bikeability index to a study area?
4. To analyze differences in bikeability index values in a case study	4.1. Which TOD nodes have highest and lowest bikeability index? 4.2. Why TOD nodes have high and low bikeability index?
5. To analyze the differences of bikeability index value and indicators score in different spatial scales of TOD area	5.1. Which indicators score that affected significantly if the spatial scales are changed?

2. LITERATURE REVIEW

2.1. Transit-Oriented Development

Transit Oriented Development concept was first introduced by Calthorpe (1993). Considered as a pioneer of TOD concept, Calthorpe has defined TOD as "… a mixed-use community within 2000 feet (around 600 meters) walking distance of a transit stop and core commercial area. TODs mix residential, retail, office, open space, and public use in a walkable environment, making it convenient for residents and employees to travel by transit, bicycle, foot or car" (Calthorpe, 1993, p.56). A walkable environment is the key concept of TOD. According to Calthorpe, encouraging people to walk can reduce the usage of the car, including a walk to and from to transit nodes.

The indicator to measure TOD which called 3D's were proposed by Cervero and Kockelman (1997) which are density, diversity and design and followed by two more indictors which are destination accessibility and distance to transit (Ewing et al., 2009; Ewing & Cervero, 2001) completed the 5D's of the TOD's built environment.

Density is measured as the variable of interest per unit of area. The variable of interest can be population, employment, building floor area, dwelling units, etc.

Diversity measures pertain to the number of different land uses in a given area. A low value indicates single-use of land and higher values more varied land uses.

Destination accessibility measures ease of access to trip attractions.

Distance to transit is measured as an average of the shortest street routes from the residences or workplaces to the nearest transit nodes in an area.

Design variables relate to characteristics of the street, pedestrian and cycling provision and site design that attract people to walk and to cycle. A design of the street that promotes walking and cycling are factors that increase the TOD-ness of the transit nodes. The environmental aspects (or characteristics) that support walking and cycling activity are deemed as the factors that increase the transit usage. The public space for walking and cycling needs to be well designed so that they are attractive, inviting and feel safe for all ages.

Some studies aimed to assess the performance of a TOD area. Evans & Pratt (2007) developed a TOD index to measure the "TOD-ness" of urban development in some cities in the USA. Likewise, Singh (2015) developed a TOD index to assess the TOD-ness of the areas around the 21 train stations that compose the TOD of the region Arnhem-Nijmegen, in the Netherlands. High TOD levels imply higher transit orientation or TOD-ness. Assessing the current TOD level of an area is, therefore, helpful in the understanding of how transit-oriented an area is and because of what reasons.

2.2. Measuring Bikeability in a TOD environment

Several methods to measure bikeability have been developed in the past, and all methods revised (Table 2) to measure bikeability based on the attributes of cycling facilities, combining these into a score. Terms commonly used are *index, level of service, rating and score*. The purpose of these studies was to measure bikeability in a study area, based on indicators. Some studies measured bikeability of particular cycling path (Botma, 1995; Davis, 1995; Dixon, 1996; Epperson, 1994; Jensen, 2007; Landis, 1994; Petritsch et al., 2007; Sorton & Walsh, 1994; *The Highway Capacity Manual*, 2011) whereas other studies focused on the condition of the road or area in order to build new cycling lanes (Emery & Crump, 2003; Krenn, Oja, & Titze, 2015; Lowry et al., 2012; Mesa & Barajas, 2013; Turner, Shafer, & Stewart, 1997). All the studies listed on Table 2 develop indicators to measure bikeability.

Table 2. Literature review on Bikeability measurement methods

Method	Reference
Bicycle Stress Level	Sorton & Walsh (1994)
Road Condition Index	Epperson (1994)
Interaction Hazard Score	Landis (1994)
Bicycle Suitability Rating	Davis (1995)
Bicycle Suitability Assessment	Emery and Crump (2003)
Bicycle Suitability Score	Turner et al. (1997)
Bicycle Level of Service Score	Lowry et al. (2012)
Bikeability Index	Mesa and Barajas (2013); Krenn et al. (2015)
Bicycle Level of Service	Botma (1995); Dixon (1996); Jensen (2007); Petritsch et al., (2007); The Highway Capacity Manual (2011)

Some factors will encourage bicycle ridership while others are obstacles to cycling. As an example is a study by Rybarczyk and Gallagher (2014) which looked into walking and cycling at a metropolitan commuter university. They indicated that safer bicycle routes, better lighting, and visible bicyclists would encourage faculty, staff, and students to cycle. Additionally, some factors were identified as obstacles to cycling such as inclement weather, reduced bicycle security, crime, fear about personal safety and lack of bicycle lanes.

The development of an index in different study areas considers the factors that are important and significant for the areas. Mesa and Barajas (2013) developed a bikeability index for Cali, a city in Colombia, which take four factors into account: infrastructure, environmental quality, topography, and security. The methodology to develop the model involves weighted regression. Because of lack of cycling infrastructure, this factor was seen as unimportant for cyclists. Likewise, topography was considered as an unimportant factor because this area has mild slopes.

Krenn et al. (2015) developed a bikeability index to assess the bicycle-friendliness of urban environments and visualize it on a bikeability map based on Geographic Information System (GIS) data. The variables included in this bikeability index are cycling infrastructure, the presence of separated bicycle pathways, main roads without parallel bicycle lanes, green and aquatic areas and topography. Three environmental components (cycling infrastructure, bicycle pathways, and green areas) were positively related, and two components (main roads, and topography) were negatively related to the used route.

In the Netherlands, where natural conditions and infrastructure are conducive, the bicycle is a potentially attractive access for railways since it allows travelers to avoid waiting at bus, metro or train stops (Rietveld, 2000). According to Bach (2006), five aspects should be considered for cycling infrastructure design: coherence, directness, attractiveness, safety, and comfort.

The study by Dill (2004) shows that connectivity as the general purposes of transportation network which links people and their destination. The connectivity of cycling network which regards to the directness and the coherence aspects can be considered as the criteria of bikeablity index. Based on the study, for measuring connectivity, the indicator that is used are intersection density, cycling path density, and cycling route directness.

Based on those studies, table 3 summarizes the indicators used to measure bikeability. It can be concluded that the most common indicators are traffic volume, traffic speed, the width of through lane, pavement quality, and topography. Therefore, a traffic condition and infrastructure aspects are seen as the most important criteria to measure bikeability.

2.3. Bicycle as a feeder mode to transit

The last session revised literature about measuring bikeability. However, the focus of this study is the bikeability around a TOD area, when the bicycle is considered as a feeder mode to transit. A study by Advani and Tiwari (2006) about bicycle as a feeder mode for bus service in New Delhi, India shows that the cyclists in this area do not use their bicycle to reach a bus stop, for the following reasons: the absence of parking facilities in bus transit; the short distance from their origin to the bus stop; the lack of safe cycling facilities along the traffic roads. In addition, bicycle parking and other cycling facilities are also required to encourage people to use bicycle from their origin to the transit. Survey results show that 91% of bicycle owners and 45% of the total bus commuters who do not own bicycle are potential users if bicycle friendly infrastructure would be provided. In addition, bicycle-to-transit services (trails, on-road bike lanes, and bike parking) will enlarge the catchment of transit area because public modes will be reachable by people who are beyond walking distances to transit stops.

Intermodality is also seen as a way to integrate the non-motorized modes with public transportation. For this integration to be successful, it is crucial the provision of cycling lanes along the road and also good quality of bicycle parking (including security of the bicycles, protection from the weather, appropriate location, ease of use and low-cost or no-cost bike parking) (Salleh et al., 2014). In addition, some programs should be proposed such as the bicycle sharing (rental bikes) and the provision of bicycle hubs, with showers, changing room, bicycle repair stations, and cafes.

In Netherlands, all major and secondary cities in the Netherlands are connected by the national railway system. Cycling is by far the most important access mode to this system. The study by Kager, Bertolini, and Brömmelstroet (2016), which explore the distinct characteristics of bicycle-train combination in Netherlands, conclude that cycling increase the catchment area of the train stations significantly.

In the Netherlands, parking facilities around stations are very common, providing space for the cyclists to store their bicycle prior to the travel by bus or train. However, some stations are not able to provide proper conditions of parking facilities, for example, because it has reached its full capacity, as Figure 1 shows. Therefore, parking criteria should also be included for measuring bikeability around a TOD area. Parking at the stations is seen as one important aspect of intermodality. The study by Van der Spek and Scheltema (2015) confirm that bicycle storage management at the train stations is important to replace car trips by cycling trips.

Figure 1. Bicycle parking in Utrecht train station.
Source: https://idonotdespair.com

Table 3. Identified indicators

No.	Indicators	Sorton & Walsh (1994)	Epperson (1994)	Landis (1994)	Davis (1995)	Botma (1995)	Dixon (1996)	Emery and Crump (2003)	Turner et al. (1997)	Jensen (2007)	Petritsch et al., (2007)	HCM (2010)	Lowry et al. (2012)	Mesa & Barajas (2013)	Krenn et al. (2015)	Rybarczyk & Gallagher (2014)	Dill (2015)
1	traffic volume	x	x	x	x	x		x	x	x	x		x				
2	number of through lanes										x	x					
3	traffic speed	x	x	x	x		x	x	x	x	x	x	x				
4	curb lane width	x	x						x								
5	pavement quality		x	x	x			x	x			x	x				
6	generation of conflicting travel paths		x				x										
7	land-use (build-up area)			x						x							
8	curb cut frequency			x													
9	presence of heavy vehicles			x							x	x					
10	width of outside through lane			x	x			x			x	x					
12	condition of location (topography)				x			x					x				
13	path width					x		x									
14	type of traffic (cycling)					x											
15	perceived hindrance of the users					x											
16	basic facility provided						x										
17	motor vehicles LOS						x										
18	maintenance						x										
19	intermodal links						x										
20	width of buffer area									x							
21	passed pedestrians per hour									x							
22	parked motor vehicle on nearest roadside									x							
23	parking occupancy											x					
24	mid-segment demand flow rate											x					
25	width of paved outside shoulder											x					
26	presence of curbs											x			x		
27	environmental quality (EQI Index)													x			
28	road safety and maintanence													x			
29	personal safety (security)													x			
30	presence of separated bicycle pathways														x		
31	main roads without parallel bicycle lanes														x		
32	green and aquatic areas														x		
33	lighting															x	
34	connectivity																x

3. METHODOLOGY

This research applies a quantitative method to develop indicators to measure bikeability around a TOD area. There are two main steps in this research: index formulation and application of the index on the study area. For index formulation, a literature review about existing methods for measuring bikeability is conducted, followed by collecting data, selecting and measuring criteria (and the indicators), normalizing the indicator's score and weighting the indicators. On the data collection step, the methods will include desk study (gathering the spatial data) and survey in the study area for collecting remaining data.

On the application index step, data will be processed and analyzed to calculate the bikeability indexes for the various TOD nodes of the study area. The index calculation will be implemented for three different buffer distances. Figure 2 summarizes the methodology applied in this research.

Figure 2. Methodology of the research

The study area is the Dutch city region of Arnhem and Nijmegen has 21 train stations that make part of a TOD network (Figure 3). The bikeability index will be calculated for all 21 stations.

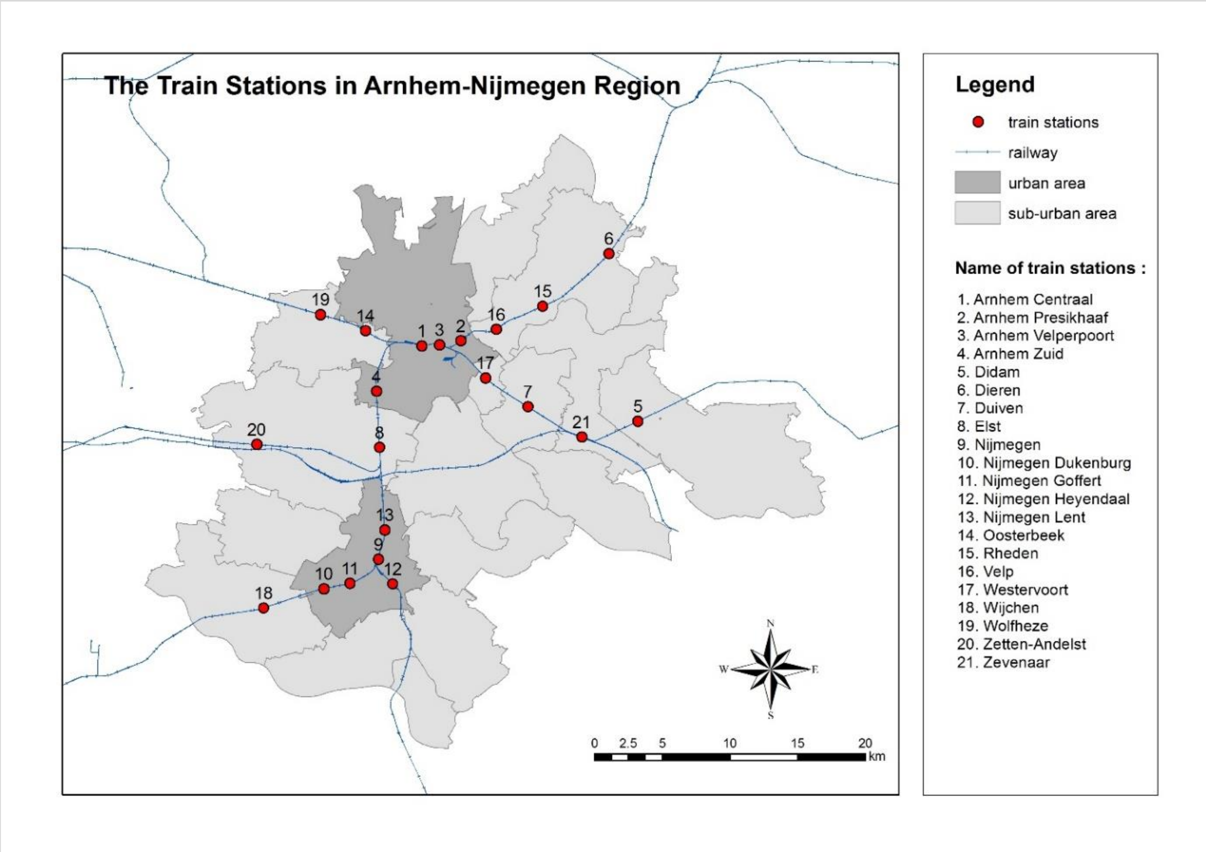

Figure 3. Train stations in Arnhem-Nijmegen region

On this research, spatial data about bicycle infrastructure was purchased from Fietsersbond (2016), the Dutch cyclist union. The data include all types of roads, those allowed and also forbidden for cyclists. However, for the present study, only the segments allowed for cycling were considered. All the spatial data, as well as the metadata, is available in Dutch.

3.1. Index Formulation

Index formulation is the first step in this research and consists of three steps: 1) assigning the TOD area, 2) selecting and measuring indicators, 3) normalizing the score and weighing the indicators.

3.1.1. Assigning the TOD area

TOD areas are generally located within a radius of one-quarter to one-half mile (400 to 800 m) from transit stop, corresponding to 5 minutes or 10 minutes walking, respectively. For this research, because the focus is on cycling to train stations, the spatial scale needs to be extended. In this study, three spatial scales were chosen to be analyzed, with radius 800, 1600 and 2400 meters in order to assess built environment characteristics in the immediate surrounding of the train stations, and with equal intervals between scales.

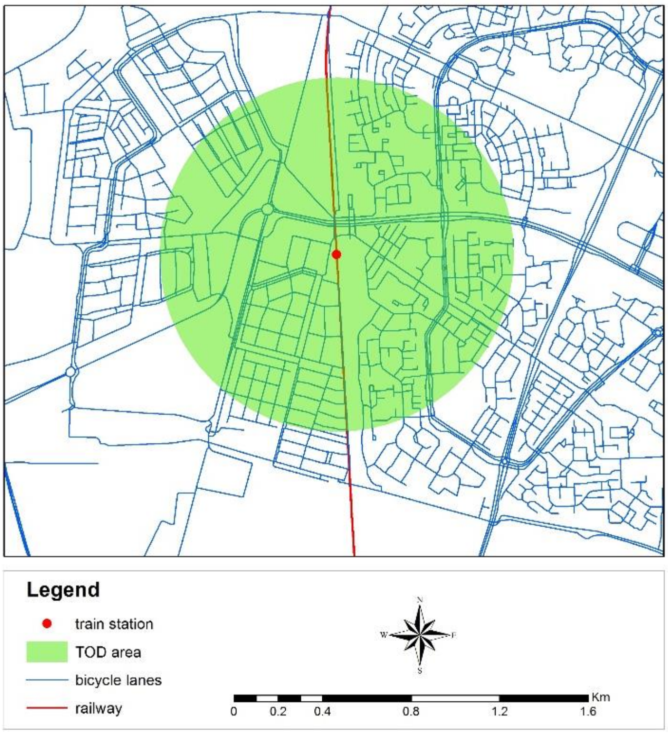

Figure 4. Example of a TOD area (800 meters)

In some cases, the TOD areas are overlapped with others because the distance between the train stations is smaller than the radius of the TOD area. This overlapping was not considered as a problem because the assessment is still on all bicycle lanes around train stations. Thus the presence of other stations in those areas was not taken into account in the calculations. The consequence of this treatment is that some bicycle lanes are used more than once for the calculation. Figure 5 shows an example of overlapped TOD areas.

Figure 5. Example of overlapped TOD areas

3.1.2. Selecting and Measuring Indicators

Based on the literature review, a list of criteria and indicators for measuring bikeability around TOD nodes was identified. Also, this research will use the five principles of cycling infrastructure design as developed by Bach (2006) (coherence, directness, safety, attractiveness, and comfort) to classify the selected criteria and indicators within the framework composed by these five aspects.

In the present bikeability index formulation, the following nomenclature has been used: selected **criteria** is defined as a rule or principle for evaluating or testing something. To measure the criteria, **indicator(s)** (one or more) are developed, which are attributes of each criterion. Each indicator has a **measurement** method. Each measurement has **measurement variables** that contribute to the measurement process. Each measurement variable is represented by levels. On this formulation, the **variable level** value is given based on the service level. The highest value is 1 which means that the variable approach the ideal condition. The lowest value is 0, which means that the variable is far from the ideal condition. The **criteria, indicators, measurement, measurement variables,** and **variable level** are shown on Table 4.

The attributes of the spatial data acquired from the Dutch Cycling Union were translated from Dutch into English. After data cleaning, only the segments corresponding to cycling lanes were considered for the analysis, i.e., the roads that are not allowed for cycling were excluded. However, attributes of the motorized traffic (such as maximum speed) are also present on the attributes of the cycling network. Other useful attributes of the dataset are related to traffic disruption, road type, quality of road surface, street lighting, water, aesthetics, inside build up area, green area, and maximum slope.

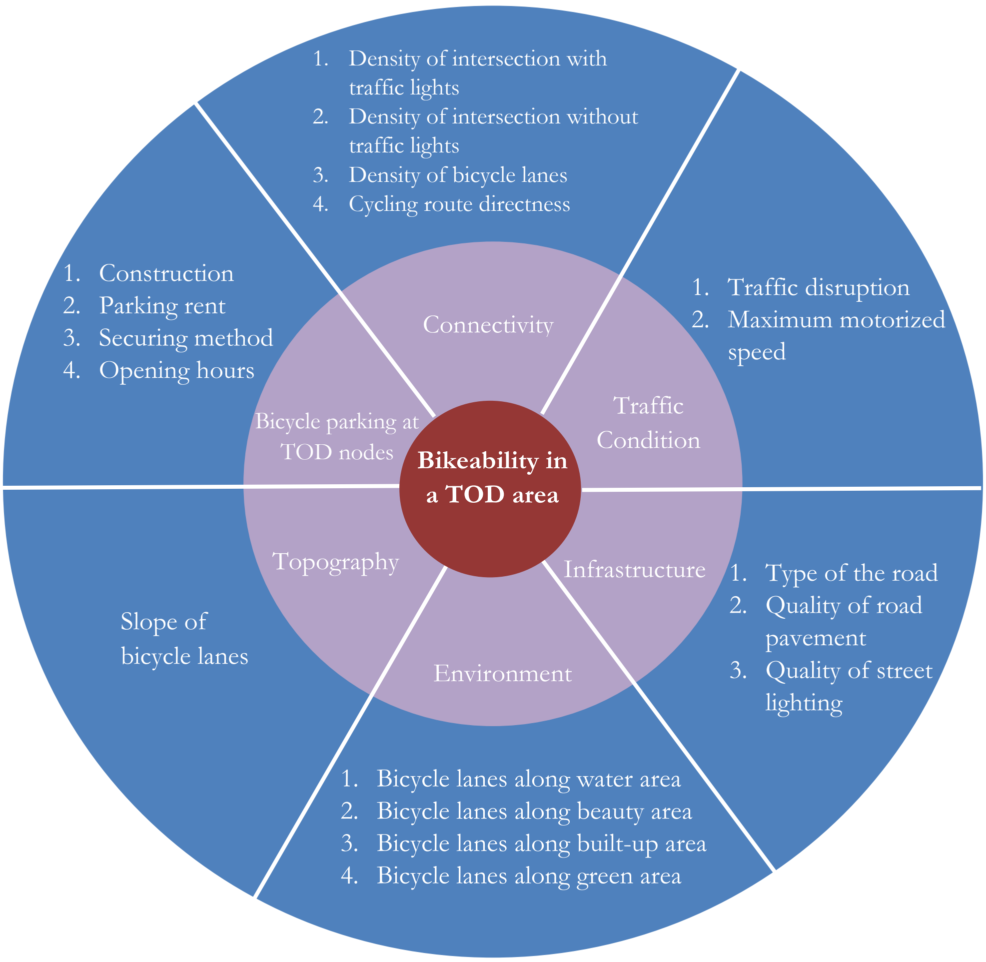

Figure 6. Bikeabilty Index in a TOD area

Table 4. Selected criteria, indicators, measurement methods, measurement variables and variable levels

Criteria	Indicators	Measurement	Measurement Variables	Level
1. Traffic condition	Maximum motorized speed	Ratio of bicycle lanes with low maximum speed of motorized	Ratio of bicycle lanes on the road with maximum speed 30 km/h	1
			Ratio of bicycle lanes on the road with maximum speed 50 km/h	0.67
			Ratio of bicycle lanes on the road with maximum speed > 50 km/h	0.33
	Traffic disruption	Ratio of the bicycle lanes with few traffic disruption	Ratio of the bicycle lanes with few traffic disruption	1
			Ratio of the bicycle lanes with reasonable traffic disruption	0.67
			Ratio of the bicycle lanes with many traffic disruption	0.33
2. Connectivity	Intersection with traffic lights density	Density of intersections with traffic light	Density of intersections with traffic light	-
	Intersection without traffic lights density	Density of intersection without traffic light	Density of intersections without traffic light	-
	Bicycle lanes density	Bicycle lanes density	Bicycle lanes density	-
	Cycling Route Directness	Cycling Route Directness	Cycling Route Directness	-
3. Infrastructure	Type of the road	Ratio of bicycle lane on the road	Ratio of solitary bike path (the buffer with the road > 30 m)	1
			Ratio of bicycle path along the road (with physical separation)	0.80
			Ratio of road with bicycle lane (strip marked)	0.60
			Ratio of normal road (with car, no bicycle path)	0.40
			Ratio of service road	0.20
			Ratio of pedestrianized road	0.10
	Quality of road pavement	Ratio of good road pavement	Ratio of good road pavement	1
			Ratio of reasonable road pavement	0.67
			Ratio of bad road pavement	0.33
	Quality of street lighting	Ratio of good light bicycle lanes	Ratio of good light bicycle lanes	1
			Ratio of limited light bicycle lanes	0.67
			Ratio of no light bicycle lanes	0.33
4. Environment	Bicycle lanes along water area	Ratio of bicycle lanes along water area	Ratio of bicycle lanes with water area	1
			Ratio of bicycle lanes without water area	0.50
	Bicycle lanes along beauty area	Ratio of bicycle lanes along beauty area	Ratio of bicycle lanes with beautiful area	1
			Ratio of bicycle lanes with neutral area	0.67
			Ratio of bicycle lanes with ugly area	0.33
	Bicycle lanes along built-up area	Ratio of bicycle lanes along built-up area	Ratio of bicycle lanes with built-up area	1
			Ratio of bicycle lanes without built-up area	0.50
	Bicycle lanes along green area	Ratio of bicycle lanes along green area	Ratio of bicycle lanes in built-up area with a lot of green area	1
			Ratio of bicycle with little of green area	0.50
5. Topography	Slope percentage of bicycle lanes	Ratio of bicycle lanes with low slope percentage.	<1%	1
			1-2%	0.75
			2-4%,	0.50
			> 4%	0.25

Criteria	Indicators	Measurement	Measurement Variables	Level
6. Bicycle parking	Quality of bicycle parking condition the station	Construction	Indoor	1
			Outdoor	0.5
		Parking rent	Free	1
			Paid	0.5
		Securing method	Guarded	1
			Bicycle lockers	0.75
			Unguarded	0.5
		Opening hours	24 hours	1
			< 24 hours	0.5

Criteria 1: Traffic condition

Traffic condition is one of the criteria to measure the bikeability. The good condition of the traffic will support the safety and comfort cycling. The indicators are selected to measure this criterion is maximum motorized speed and traffic disruption.

1. Maximum speed of motorized vehicles
   The road with a low speed of motorized vehicles will increase the safety of the cyclists. The selected measurement method for this indicator was the ratio of cycling lanes next to roads with low maximum speed, measured by the length of the bicycle lanes with low maximum speed divided by the total length of the cycling lanes in TOD area. In the Netherlands, inside built-up areas the maximum speed is 30km/h or 50km/h, and outside the built-up area the values may differ, but they are all above 50km/h. Three classes of maximum speed are then considered in this study: 30, 50, and above 50 km/h. The variable levels are 1, 0.67 or 0.33, meaning that the roads with maximum speed 30 km/h are the safest and assume the value equal to 1; whereas for 50km/h the value is 0.67 and finally, roads with higher maximum speeds assume the lowest value, equal to 0.33.

   To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each of the three maximum speed levels then multiplied by its variable level, summed up, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(30\ km/h\ \ length * 1) + (50\ km/h\ length * 0.67) + (> 50\ km/h\ length * 0.33)}{total\ length}$$

2. Traffic disruption
   Traffic disruption is considered as the indicator because the few of traffic disruption will increase the safety and comfort of the cyclists. Traffic disruption is the 'delay and/or danger due to the physical presence of other traffic' (Fietsersbond, 2016). 'Other traffic' can consist of moving or parked cars, mopeds, other cyclists, pedestrians or any combination of these.

   The measurement method of this indicator is the ratio of bicycle lanes with few, reasonable or many traffic disruption. The calculation of the ratio is given by the length of bicycle lanes on one of the three categories of traffic disruption, divided by the total length of bicycle lanes in TOD area.
   This measurement is classified into three categories based on the level of disruption:

a. Few traffic disruption:
   - roads that are busy, but with separate, spacious and well-organized bicycle paths
   - roads in 30 km/hours zones, quiet
   - very quiet roads (even in rush hour and on Sunday afternoon) which must not be driven faster than 60 km/hours

b. Reasonable traffic disruption:
   The bicycle lanes with traffic disruptions are categorized as busy, narrow, or winding roads with separate cycle paths although separate bicycle paths are still fairly chaotic traffic conditions. For example, because of the many crossing for cyclists in side streets. Example: roads through industrial areas with many exits with freight traffic.

c. Many traffic disruption
   The bicycle lanes which are categorized with many of traffic disruptions is the lanes with many of danger or not possible to at normal speed of cycling. There is no separate bicycle lanes and busy roads with the partial one-way street (cyclist may against the traffic flow). Example:
   - 50 km/hour- busy city roads without separate cycle paths;
   - busy narrow 80 km/hour-roads outside built-up areas with or without bicycle lanes;
   - a separate bike path along a road through the city with very many children's crossing pedestrian (shopping streets) and/or loading and unloading operations.

The variable levels are 1, 0.67 or 0.33, meaning that the roads with few traffic disruption are the safest and assume the value equal to 1; whereas for reasonable traffic disruption the value is 0.67 and finally, roads with many traffic disruption assume the lowest value, equal to 0.33.

To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each of the three traffic disruption level then multiplied by its variable level, summed up, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(few\ length * 1) + (reasonable\ length * 0.67) + (many\ length * 0.33)}{total\ length}$$

Criteria 2: Connectivity.

The connectivity is the important criterion to support the coherence and directness. Street connectivity is the primary component for the good neighbourhood. For measure the connectivity of bicycle lanes, four indicators are assessed to measure it which are intersection with traffic lights density, intersection without traffic lights density, cycling lanes density, and cycling route directness.

1. Intersection density (with and without traffic lights)

   Intersection density is the number of intersections per unit area, e.g. square mile. To measure the connectivity, the intersections are divided into two types: intersection with traffic lights and without traffic lights. On the equal weight calculation method, there is no difference calculation for both types. This separation is used on the unequal weight calculation because those types probably have different weights. A higher number of densities of intersections with and without traffic lights indicate more stops which assumed lower connectivity.

For measuring those densities, the roads allowed for bicycle are selected. Another data which needed for this measuring is the nodes data in TOD area. Using "select by location" in ArcGIS, those nodes are selected. On this data, the nodes divided into three nodes type: intersection without traffic lights , intersection with traffic lights and cul de sacs. Because the measurement is about the connectivity, the cul de sacs are excluded from the measuring process. After excluding it, the nodes data only have two types: intersection without traffic lights and intersection with traffic lights. After each type intersection is produced, the density value can be calculated with divided number of intersection by the area in square kilometers. The intersection density is assigned as the score for those indicators. This indicator contributes negatively to bikeability index because the higher score will decrease the index.

$$Score\ \ (with\ traffic\ lights) = \frac{number\ of\ intersection\ with\ traffic\ lights}{total\ TOD\ area}$$

$$Score\ \ (without\ traffic\ lights) = \frac{number\ of\ intersection\ without\ traffic\ lights}{total\ TOD\ area}$$

2. Bicycle lanes density
   Cycling lanes density is measured as the number of linear of cycle lanes per square of land (or kilometers per square kilometer). A higher number would indicate more cycling lanes, and presumably, higher connectivity. The method to measure this indicator as same as to measure intersection density.
   To measure this density, first, exclude the road/links that not allowed for bicycle. Therefore, the assessment only for the road that allowed for bicycle. Then the total length of the lanes in the TOD area of each station is summed. The total length (in km), is divided by the total area (in square kilometers). It calculates the density of bicycle lanes in km/km^2. The bicycle lanes density is assigned as the score for this indicators.

$$Score\ (bicycle\ lanes\ density) = \frac{total\ length\ of\ bicycle\ lanes}{total\ TOD\ area}$$

3. Cycling route directness (CRD)
   The cycling route directness is the shortest path distance divided by straight-line distance. A lower number indicate higher connectivity. The lowest value of CRD is 1, which means that the high connectivity is when the shortest path distance is the same as straight-line distance. For measure it, the pairs of origins and destinations within the TOD area are selected. The center of each building in the area (BAG data) as the origins and train stations as the destination. The total of cycling route directness (CRD) is average shortest path distance divided by the average of straight-line distance.
   First stage of calculation, the straight-line distance of each building will be calculated. To represent the building, the center points of each building and train stations are created (BAG data). The straight-line distance from each building to the train stations is calculated with the "point distance" analysis in ArcGIS. The result of this analysis is a table showing the distance from each center point of building in TOD area to the train stations.
   The next stage is to calculate the shortest path from each center point each building to the train stations. For the first develop the *network dataset* using roads data. To develop this network dataset, the access

and direction of the bicycle on the road must be considered. For this requirement, one extra attribute is added to the road data, which is named "Oneway". The codes of this attribute is the *accessibility* field, which can be seen on table 5.

Table 5. Oneway field values

Accessiblity	Oneway	Meaning
Both	<Null>	Bicycle allowed pass in both directions
No	N	Bicycle not allowed pass in any direction over this segment
Away	FT	Bicycle allowed pass the segment only in the direction as the segment was digitized (From –To)
Back	TF	Bicycle allowed pass the segment only in the opposite direction as the segment was digitized (To – From)

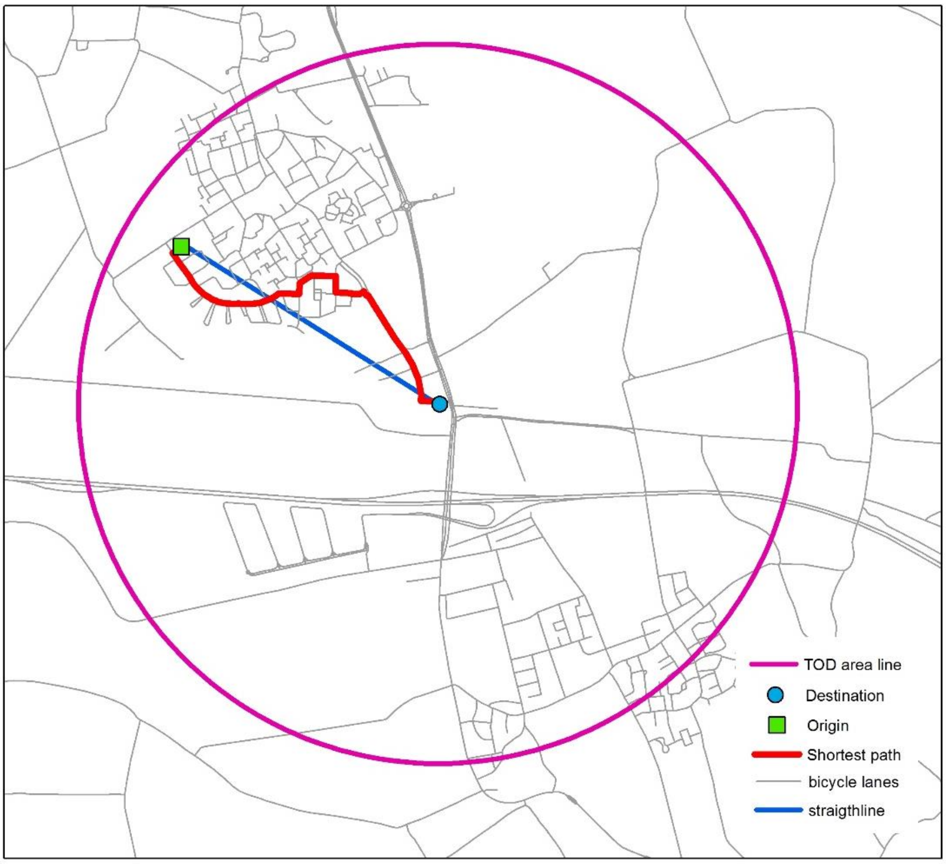

Figure 7. Cycling route directness

Besides the access and direction, for the developing the network datasets, *the costs* are considered. The costs can be either time or length. On this CRD calculation, length is used as the cost because we want to compare the distance of straight-line and the shortest path.

After developing the network dataset, the next step is using *network analyst* to calculate the shortest route distance from each building to train stations. From the several network analyst types, *Closest Facility* has selected which bicycle parking on stations as *the facilities*, center points of the building as *the incidents* and

TOD area line as *the barriers*. Bicycle parking is chosen as the facilities, not center point of train stations, because the bicycle parking location is more than one in some stations and the cyclist will choose the location which closest from the origin. TOD area line is selected as the barriers because the calculation is restricted to the train stations and its TOD area. As the results, each center points of the building will have the shortest route distance to train stations (bicycle parking). As a result, we have an average of cycling route directness (CRD) as the score. This indicator contributes negatively to bikeability index because the higher score will decrease the index.

$$Score\ (average\ CRD) = \frac{average\ shortest\ path\ distance}{average\ straight\ line\ distance}$$

Criteria 3: Infrastructure

The good conditions of infrastructure influence the cycling activity, as it is commonly linked with safety and comfort. For measure this criterion, three indicators are selected which is considered as the appropriate indicator: type of the road, quality of road surface and street lighting

1. Type of the road
   Type of the road is regard to the condition of the road to provide the cycling lanes for the cyclists. Type of the road affects cycling because the each type provides the different facilities. The measurement method is the ratio of solitary bicycle lanes. On this indicator, six types of the road are used as measurement variables which are solitary bicycle lanes, bicycle path along a road, road with bicycle lanes (with strip marked), normal road, frontage road and pedestrianized road. Each type is given the value, which shows the level of the ideal condition for bicycle. The highest value is solitary bicycle lanes because the facilities of this type are the closest the ideal condition to cycle. The lowest value is given to pedestrianized road because of cyclists limited accesibility in this road type. The types of the roads are shown in figure 2.

   To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each of the six types of road then multiplied by its variable level, summed, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(solitary * 1) + (along\ road * 0.8) + (strip\ marked * 0.6) + (normal * 0.4) + (frontage * 0.2) + (pedestrianized * 0.1)}{total\ length}$$

 **Solitary bicycle lanes** Source: www. fietsennaarschool.fietsersbond.nl	 **Bicycle path along a road** Source: www.breda.nl
 **Road with bicycle lanes (with strip marked)** Source: www.fietsersbondheezeleende.dse.nl	 **Normal road** Source: www.sabre-roads.org.uk
 **Frontage road** Source: http://www.houstonfreeways.com	 **Pedestrianized road** Source: www.amsterdam.nl

Figure 8. Type of road

2. Quality of road surface

For measure about the quality of road surface, ratio bicycle lanes with good quality of road surface is used as the measurement methods. The number of ratio is measured by the length good road surface of bicycle lanes divided by the total length of bicycle lanes on TOD area. Because this quality divided on three level, value each level is given the based on level of service: good = 1, reasonable = 0.67, bad = 0.33. The categories of conditions of the road surface can be explained as:

a. Good quality
An asphalt road, pavement or road made out of is ' good ' as an even better quality and no advantage for a cyclist on a simple classic city bicycle. On that city bicycle, cyclist experience no vibration nuisance

b. Reasonable quality
An asphalt road is ' reasonable ' if there are obvious defects such as cracks and holes in the surface (up to 2 cm deep).

c. Bad quality
An asphalt road is ' bad ' if there are deep holes in it, or if cyclist experience a strong vibration constantly.

To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each of the three quality of pavement level then multiplied by its variable level, summed up, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(good\ length * 1) + (reasonable\ length * 0.67) + (bad\ length * 0.33)}{total\ length}$$

d. Quality of street lighting
The good quality of lighting decreases the number of cycling accidents, especially in the night. The indicators to measure this indicator are the ratio of the bicycle lanes with the good light. This ratio is measured by the length of bicycle route with good lighting divided by the total length of bicycle route on TOD areas. This indicator is classified into three levels: good lighting, limited lighting, and no light. Based on the level of the light, each category is given the value: good =1, limited = 0.67, no light = 0.33. The explanation of each category are:

a. Good
- the height of light poles less than 8 meters not exceeding 60 meters apart from one another; or if
- light masts higher than 8 meters no longer than 80 meters apart from one another.

b. Limited
- the distances between the light poles are larger. This is outside the urban area often in the form of so-called directed lighting, which occasionally in a curve or a side road or driveway stands a lamppost
- the main carriageway is illuminated, but the cycle path is still quite dark due to wide trees (in summer). This is exacerbated if the lights only state on the other side of the main road

c. No light
- no public lighting, also not on the intersections; or
- when lighted intersections so far apart that cyclist not able to see the next intersection because of their remoteness or because of curves

To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each of the street lighting level then multiplied by its variable level, summed, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(good\ length * 1) + (limited\ length * 0.67) + (no\ light\ length * 0.33)}{total\ length}$$

Criteria 4 : Environment

The environment is considered as one of the criteria because this criterion influences the comfort and the attractiveness. For measuring this criterion, four indicators are assigned: bicycle lanes along aquatic area, bicycle lanes along beauty area, and bicycle lanes along built-up area

1. Bicycle lanes along water area
   One of the indicator to measure environment is the ratio of cycling lanes without water area. .To measure it, the cycling lanes without the water areas divided by the total length of the cycling lanes on the TOD area. This indicator defined by "along" and "not along", thus, level of this variable are 1 and 0.5 respectively.
   To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length each level then multiplied by its variable level, summed, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(with\ water\ area\ length * 1) + (without\ water\ area\ length * 0.50)}{total\ length}$$

2. Bicycle lanes along beauty area
   To define the term of "beauty" is difficult because the sense of beauty is a subjective thing. The method to measure this criterion is the ratio of bicycle lanes with a beautiful sight. This ratio is measured by the length of bicycle lanes with beautiful area divided by the total length of bicycle lanes on TOD area. On the spatial data, the beauty is classified into five categories which are picturesque, beautiful, neutral, ugly and very ugly. However, for this calculation, the value of beauty is classified in three categories: beautiful (picturesque and beautiful), neutral, and ugly (ugly and very ugly). Each category is given the value based on the level of beauty, beautiful = 1, neutral = 0.67, and ugly = 0.33. The categories of beauty are explained as:
   a. Beautiful
      Include monumental building, picturesque nature, special architecture and the route without significant horizon pollution. The beauty of the route to be physically present, so no route with a beautiful sunset or with good memories. The beauty not include traffic, the green factor and traffic noise.

   b. Neutral
      The cyclists not able to decide the view is beautiful or ugly.

c. Ugly
The view along the road is boring or not interesting.

To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each beauty level then multiplied by its variable level, summed, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(beautiful\ length * 1) + (neutral\ length * 0.67) + (ugly * 0.33)}{total\ length}$$

3. Bicycle lanes along built-up area
The cycling lanes with built-up area indicate that the lanes serve people who work or live along the bicycle lanes. The indicator to measure it is the ratio of bicycle lanes along the built-up area. The equation to measure it is the ratio cycling lanes along the built-up area. To measure this ratio, the length of bicycle lanes along the built-up area is divided by the total length of the cycling lane in TOD area. This indicator defined by "along" and "not along", thus, the level of this variable are 1 and 0.5 respectively.
To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each level then multiplied by its variable level, summed, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(with\ build\ up\ area\ length * 1) + (without\ build\ up\ area\ length * 0.50)}{total\ length}$$

4. Bicycle lanes along green area
Green area is considered as the indicators for environment criteria because based on previous studies, green area is deemed as the factor which affects cyclist to choose the route. To measure this ratio the length of bicycle lanes along a lot of green is divided by the total length of the cycling lane in TOD area. In spatial data, there are six categories for green area but for the calculation, those categories are classified into a lot and a little green area. The value of "a lot of green area"= 1 and "a little of green area" = 0.5.
To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each level then multiplied by its variable level, summed, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(a\ lot\ of\ green\ area\ length * 1) + (a\ little\ of\ green\ area\ length * 0.50)}{total\ length}$$

Criteria 5: Topography
The topography of the area is one the criteria which have the impact for comfort and attractiveness aspect. The indicator to measure this criterion is slope percentage of bicycle lanes. Cyclists will avoid the area with high slope because they need more energy to cycle their bicycle. The indicators to measure this criteria is slope percentage of bicycle lanes. The method to measure this indicator is the ratio of bicycle lanes with low slope percentage. The ratio equal to the length of low slope bicycle lanes divided by the total length of bicycle lanes in TOD area. In the attribute of spatial data, there two types of slopes which are the average and the maximum. For this calculation, we use maximum slope. This indicator consists of eight categories

of slope value : <1%, 1-2%, 2-4%, > 4%. The lowest slope is given value = 1 and the highest is given value = 0.

To produce the score of this indicator, the bicycle lanes in the TOD area are selected based on the measurement variables and the total length of each level then multiplied by its variable level, summed, and divided by the total length of bicycle lanes in the TOD area. This indicator contributes positively to bikeability index because the higher score will increase the index.

$$Score = \frac{(< 1\%\ length * 1) + (1 - 2\%\ length * 0.75) + (2 - 4\%\ length * 0.50) + (> 4\%\ length * 0.25)}{total\ length}$$

Criteria 6 : Bicycle parking condition

Bicycle parking condition on the destination is one of the important factors to encourage people to use the bicycle. Because this research focus on the bicycle as the feeder mode to the transit, bicycle parking condition in the train stations is used as the criterion. The quality of bicycle parking will influence people to use bicycle because they are confident their bicycle is safe, easy to access and afford to pay the rent. For measure this criterion, four indicators are assigned which represent the condition of bicycle parking in train stations which are construction, parking rent, securing method and opening hours. All of indicators contributes positively to bikeability index because the higher score will increase the index.

1. Construction
   The definition of construction is outdoor or indoor. The cyclists prefer to park their in indoor parking because protected from the bad weather. For the value, indoor = 1 and outdoor = 0.5. For the stations which have both indoor and outdoor parking, the highest score (indoor=1) is given.
2. Parking rent
   Parking rent is one of an important factor because the cost of parking rent as the obstacles people to use their bicycle to the station. The station which the bicycle parking is free is given value = 1 and paid = 0.5. For the stations which both free and paid, the highest score (free=1) is given.
3. Securing method
   The safety of the bicycle as the consideration people to use bicycle to the train station. People prefer guarded bicycle parking than unguarded. Therefore, for the value, guarded = 1, bicycle locker = 0.75 and unguarded = 0.5. For the stations which have both guarded and unguarded, the highest score (guarded=1) is given.
4. Opening hours
   The bicycle parking which open 24 hours enable people to park or to take the bicycle whenever they arrived in station. For the bicycle parking which open 24 hours the value = 1 and the opening hours < 24 hours the value = 0.5. For the stations which have two type bicycle parking which open 24 hours and < 24 hours, the highest score (24 hours=1) is given.

Outdoor and unguarded parking

Indoor and guarded parking

Bicycle locker

Figure 9. Condition of bicycle parking in train station

3.1.3. Normalizing the scores and weighting of indicators

After all of indicators produce the scores, the next stage is normalizing with minimum and maximum values. The scores after normalization are in the range between 1 and 0. If the indicators contribute positively to bikeability index, where a higher value means positive contribution, the calculation use positive formula. The highest score of indicators is indicated with 1 and the lowest with 0. If the indicators contribute negatively to bikeability index, where a higher value means negative contribution, the calculation uses negative formula. The highest score of indicators is indicated with 0 and the lowest with 1.

$$score\ (positive) = \frac{value - lowest\ value}{highest\ value - lowest\ value}$$

$$score\ (negative) = 1 - \frac{value - lowest\ value}{highest\ value - lowest\ value}$$

The weighing is used to weight the criteria and also its indicators. For this calculation, the equal weight is implemented. The weights each criteria and indicators are shown in table 6.

Table 6. The weights of the criteria

Criteria	Weight	Indicators	Weight
Traffic condition	0.166	Maximum motorized speed	0.5
		Traffic disruption	0.5
Connectivity	0.166	Intersection with traffic lights density	0.25
		Intersection without traffic lights density	0.25
		Cycling lanes density	0.25
		Route Directness	0.25
Infrastructure	0.166	Type of the road	0.33
		Quality of road surface	0.33
		Quality of street lighting	0.33
Environment	0.166	Bicycle lanes along water area	0.25
		Bicycle lanes along beauty area	0.25
		Bicycle lanes along built-up area	0.25
		Bicycle lanes along green area	0.25
Topography	0.166	Slope percentage of bicycle lanes	1
Bicycle parking condition	0.166	Construction	0.25
		Parking rent	0.25
		Securing methods	0.25
		Opening hours	0.25

3.2. Application of the Bikeability Index on the Study Area

The next step is to demonstrate the applicability of the developed bikeability index on the study area. First, the collected data will be processed on bikeability index, which is formulated on the previous stage. The bicycle lanes that are situated within the three spatial scales will be assessed. Each indicator was calculated using ArcGIS, and input to Excel to calculate the scores. Each indicator will have a score, which will contribute to the criteria score, which in turn will contribute to the bikeability index. As a result, each of the 21 train stations will have a bikeability index, which will be obtained from the computation of all criteria and indicators scores. The procedure is repeated for three different spatial scales (800, 1600 and 2400 meters).

$$\begin{aligned} Bikeability\ Index = {} & (Traffic\ condition * 0.166) + (Connectivity * 0.166) + (Infrastructure * 0.166) \\ & + (Environment * 0.166) + (Topography * 0.166) + (Bicycle\ Parking * 0.166) \end{aligned}$$

4. RESULTS AND DISCUSSION

4.1. Differences on Bikeability Index for Three Spatial Scales

The purpose of bikeability index measurement of three different spatial scales is to review the effect of the buffers (TOD area) extension to the bikeability index. Figure 10 shows the boxplot of the bikeability index in three different spatial scales. As the explanation, the center of the plot is *median*, and in a box, the top and bottom are the limits within which the middle 50% of the score (the interquartile range, IQR). The line of the top and the bottoms are the two *whiskers* which show the top and the bottom 25% of scores (approximately). It is said 'approximately' because we have the outlier (minus 1.5 times of the IQR) which shows as circles and extreme scores (minus three times of the IQR) which show as an asterisk.

On the figure 10, it can be seen that there no significant change of bikeability index. The median, boxes size and boxes position do not change dramatically. However, the median in 2400 meters is highest, and the box is the shortest if compared with others. It can be concluded that bikeability index of 2400 meters is relatively high and the variance of the index not large.

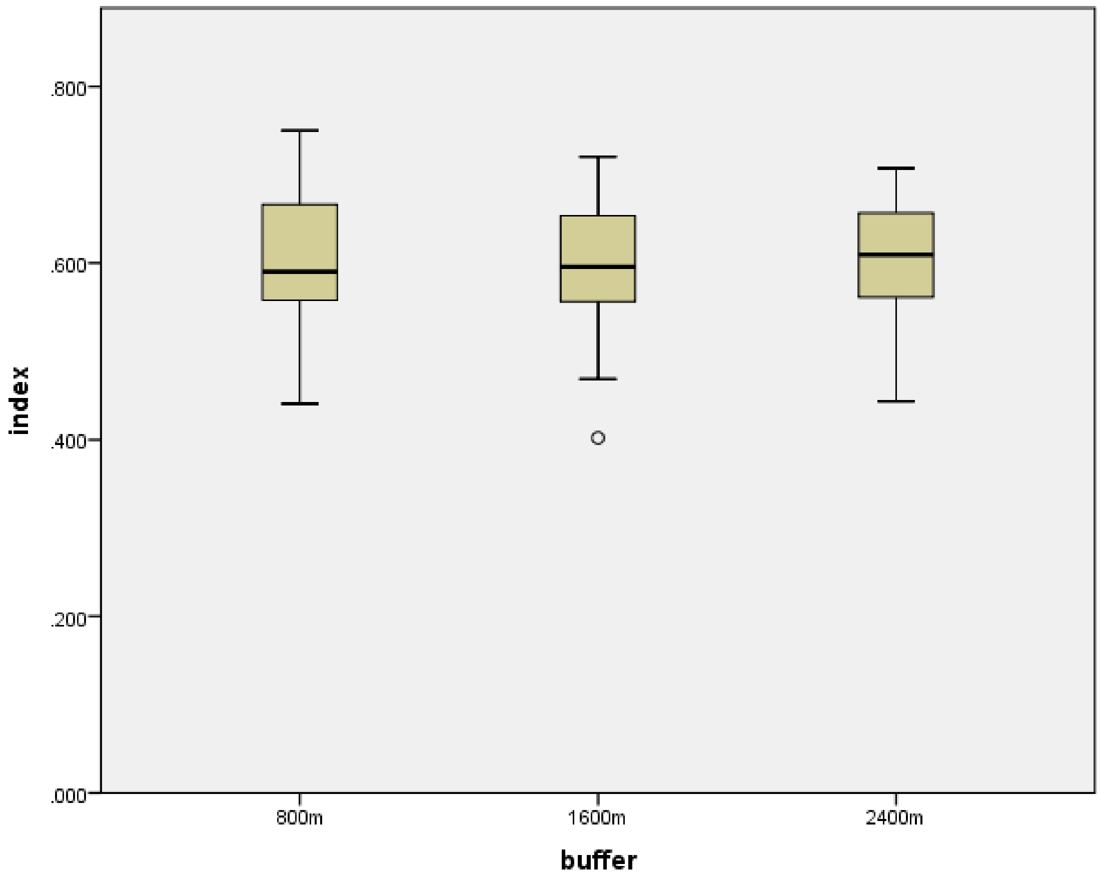

Figure 10. Boxplot chart of bikeability index in three spatial scales

4.2. Differences on Criteria for Three Spatial Scales

This section analyses the difference of the each criterion score of 21 train stations in three spatial scales. Figure 11 shows the boxplot of the score each criterion in three spatial scales, which are not including the bicycle parking because this criterion's scores are the same for three spatial scales. On the figure, if we see on the median of three spatial scales, the highest is the topography and the lowest is the environment. The boxplot of connectivity and environment seemed shorter compared others which indicate that the score of those criteria does not as vary as others. In addition, two criteria, which are infrastructure and topography, have the outlier value which indicates that there some score that very low.

The significant scores change because of buffers extension can be seen on the traffic condition and infrastructure boxplot. There are significant score change of both traffic condition and infrastructure if the spatial scales are extended from 800 meters to 1600 meters and 2400 meters. The scores of traffic condition are increase dramatically while the infrastructure scores decrease significantly. From the explanation it can be concluded that those two criteria are susceptive to the spatial scales change.

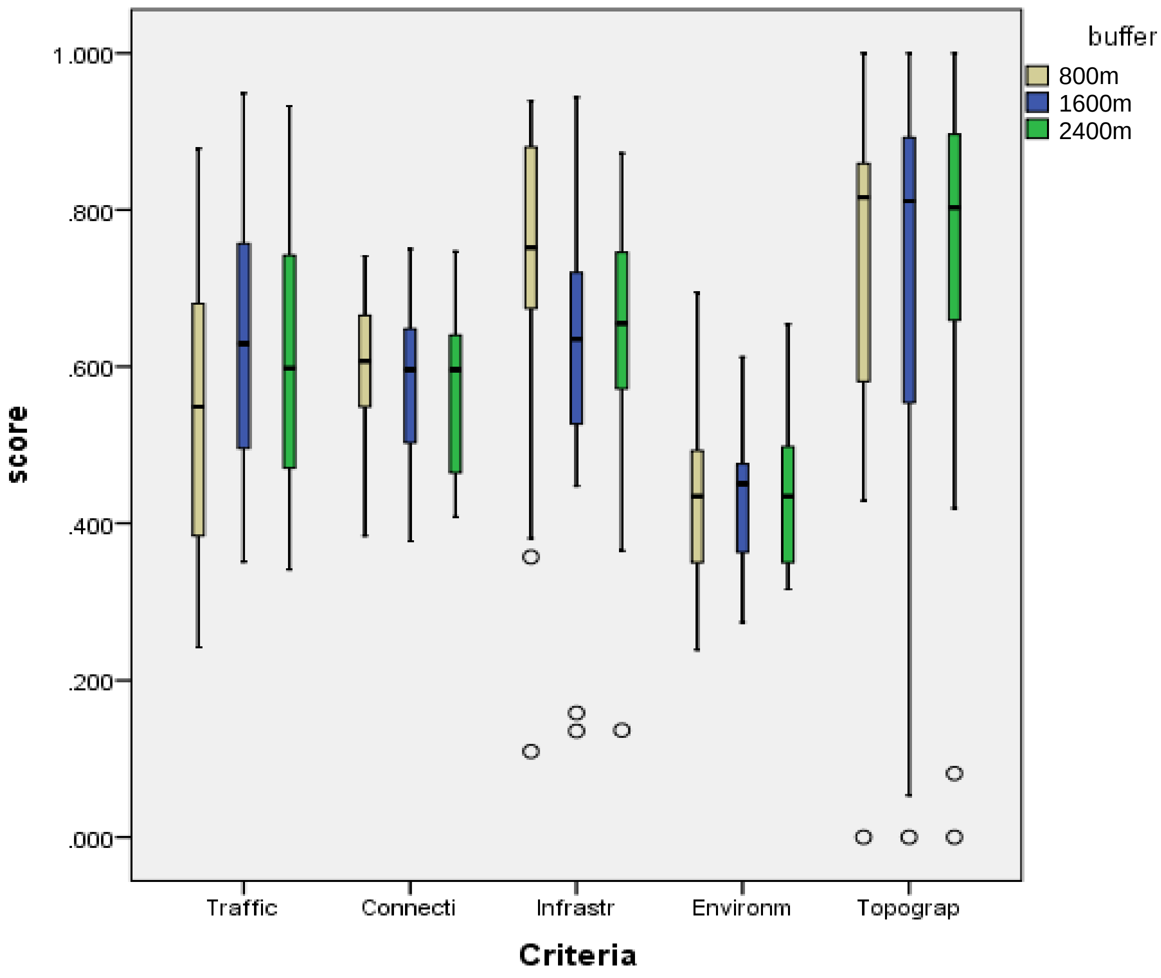

Figure 11. The boxplot of each criterion in three different spatial scales

4.3. Analysis of Stations with Highest and Lowest Bikeability Index and Criteria in Three Spatial Scales

The calculation of the indicators produce the bikeability index and the rank of each station from the largest to the lowest for three different spatial scales; 800 meters, 1600 meters, and 2400 meters.

Based on table 7, it can be seen that for the 800 meters, the highest bikeablity index is Duiven and Arnhem Zuid is placed as the highest in 1600 meters and 2400 meters. The lowest bikeability index for the 800 meters is Ooosterbeek stations and Wolfheze is the lowest positions on 1600 meters and 2400 meters. Surprisingly, Arnhem Centraal and Nijmegen as the main station in this region does not get the first position for bikeability index and all five criteria. It is interesting because those stations are expected have highest score to support the high number of cyclists which cycling from their origins to stations.

Table 7. The highest score of criteria

Spatial scale	Bikeability Index	Traffic condition	Connectivity	Infrastructure	Environment	Topography
800 m	Duiven (0.750)	Arnhem Zuid (0.878)	Oosterbeek (0.741)	Wijchen (0.940)	Duiven (0.695)	Duiven (1.000)
1600 m	Arnhem Zuid (0.720)	Arnhem Zuid (0.949)	Oosterbeek (0.750)	Wijchen (0.944)	Nijmegen Lent (0.612)	Duiven (1.000)
2400 m	Arnhem Zuid (0.708)	Oosterbeek (0.932)	Oosterbeek (0.747)	Elst (0.872)	Rheden (0.654)	Zevenaar (1.000)

Table 8. The lowest score of criteria

Spatial scale	Bikeability Index	Traffic condition	Connectivity	Infrastructure	Environment	Topography
800 m	Oosterbeek (0.441)	Arnhem Central (0.242)	Nijmegen (0.384)	Oosterbeek (0.110)	Didam (0.239)	Oosterbeek (0.000)
1600 m	Wolfheze (0.402)	Rheden (0.351)	Nijmegen (0.377)	Wolfheze (0.135)	Didam (0.274)	Oosterbeek (0.000)
2400 m	Wolfheze (0.443)	Rheden (0.341)	Nijmegen Dukenburg (0.408)	Oosterbeek (0.136)	Didam (0.316)	Wolfheze (0.000)

Besides the rank, the index can also be analyzed spatially, because it allows identifying the value of indexes based on the locations (urban or suburban). On figure 12 the location of the stations is shown, together with the calculated bikeability index value. The index was divided into three classes, represented by the colors: high (green), medium (yellow) and low (red). On the figure, it can be seen that the train stations in Arnhem-Nijmegen region by the majority have high and medium bikeability index. This value of index shows that cyclists are supported sufficiently in this area in order to reach the stations as the destination from their origins. However, Arnhem Centraal and Nijmegen as the main stations, which are expected, included as the high bikeability index only classified as the low and medium bikeability index.

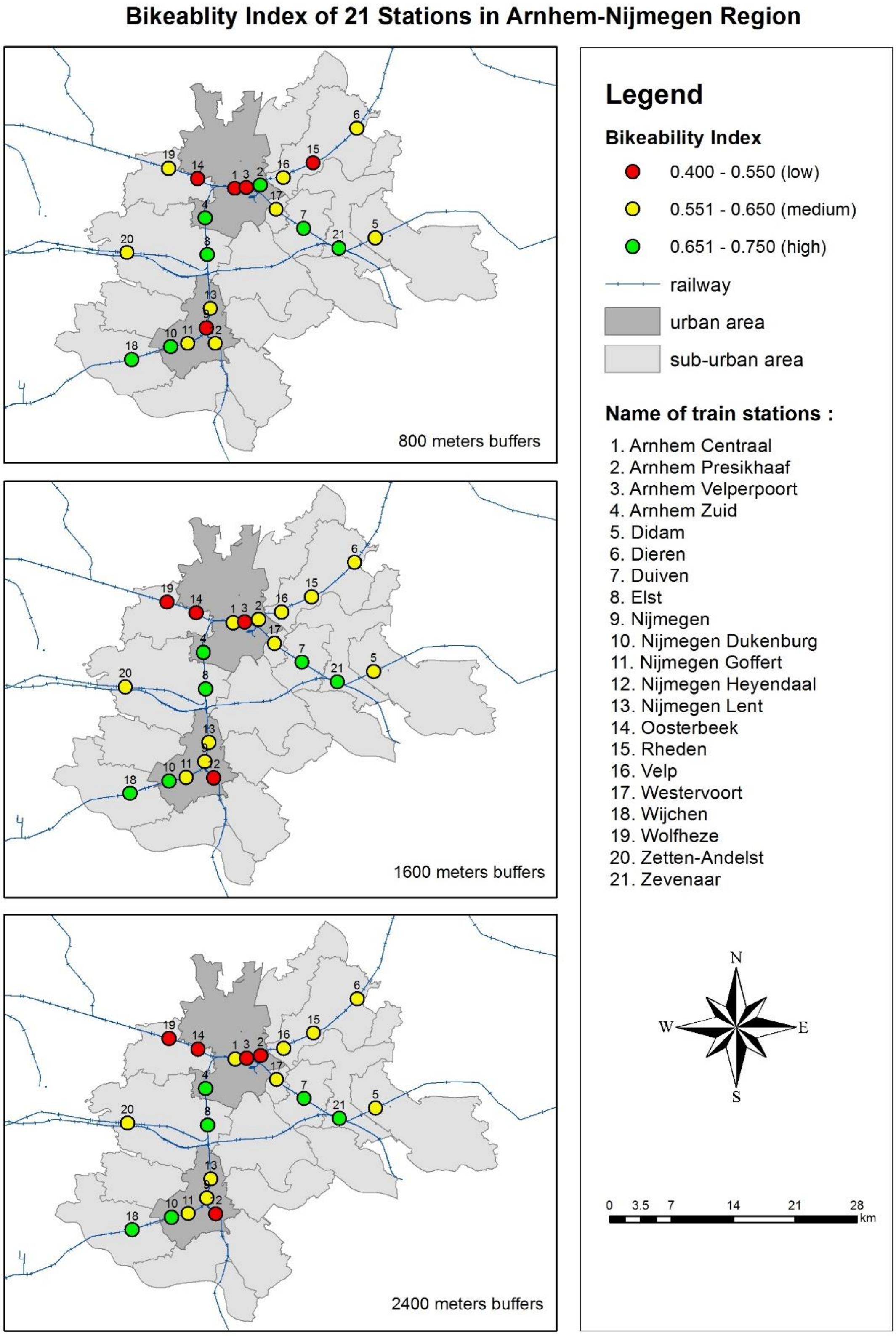

Figure 12. Bikeability index map

4.4. Analysis of Criteria for Stations with Highest an Lowest Scores in 800 meters

On this section, the analysis is focused on the score of the criteria in 800 meters spatial scale. This spatial scale is chosen because it is interesting to assess built environment and transport characteristics on the immediate surrounding of the stations.

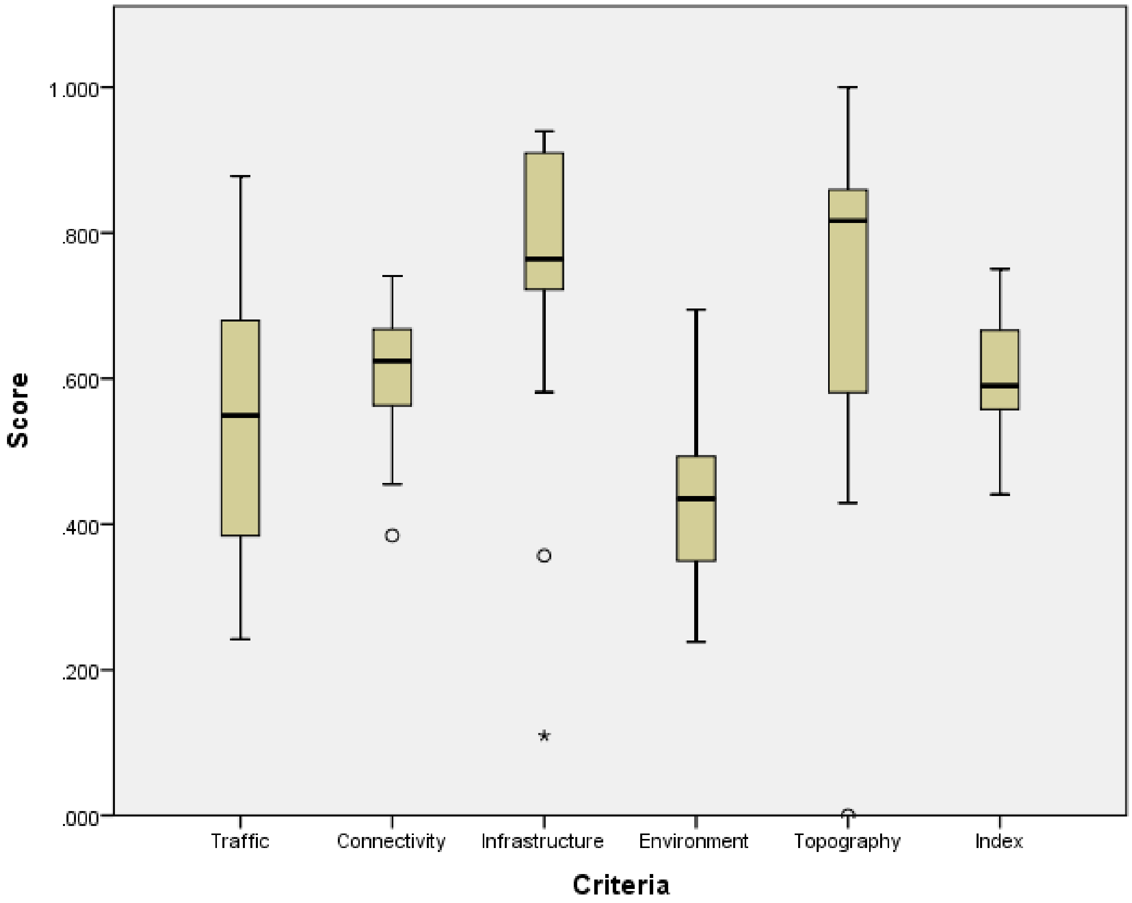

Figure 13. The boxplot each criteria scores and bikeability index

From the figure 13, it can be seen the median of the topography score is the highest and environment median is the lowest. On the both connectivity and topography, one of the scores is deemed as the outlier while the infrastructure has one outlier and one extreme score. It shows that in those criteria, some stations have very small score compared with others. The boxes show the spread of the score. It can be seen that both *traffic condition* and *topography* have the longer box compared others. It shows that variance the scores of those criteria is wider than others. The number of indicators each criterion affect this phenomenon which traffic condition consist of two indicators and topography consists of only one indicator. The normalization of the score also causes this phenomenon. The criteria with one indicator will have the chance to spread-out larger because the maximum score is 1 and the minimum score is 0. This phenomenon small possibility occurred in the criteria which have more criteria (like connectivity and environment) because the score is the combination of several indicators so that the chance to get score 1 and 0 is very small.

The six criteria contribute to measuring the index of bikeability in TOD area of each train stations. A score represents the service level of criteria. Each criteria's score is calculated from the indicator's score which is used in the measurement. Table 9 shows the train stations with the highest and the lowest score each criterion and also bikeability index. From the information of this table, the radar chart of the bikeability index and the detail map of each criteria are made. Figure 14 shows the radar charts of each the highest and lowest bikeabiltity index for each criteria. As the comparison, on that figure, the radar charts of Arnhem Centraal and Nijmegen as the main stations are showed to analyse the difference between the highest/lowest and the main stations.

Table 9. The highest and the lowest scores of each criteria

	Traffic condition	Connectivity	Infrastructure	Environ ment	Topography	Bicycle parking	Bikeability Index
Highest	Arnhem Zuid	Oosterbeek	Wijchen	Duiven	Duiven	Arnhem Centraal & Nijmegen	Duiven
Lowest	Arnhem Centraal	Nijmegen	Oosterbeek	Didam	Oosterbeek	Nijmegen Lent	Oosterbeek

On Figure 14, it can be seen that station Duiven scores highest in bikeabiity index, with scores relatively high for all criteria. On the other hand, station Oosterbeek has the lowest Bikeability Index, scores very low for topography and infrastructure, but scores relatively high for the other criteria. It can be understandable because this criteria have only one indicator whereas the others have from two to four number of indicators.

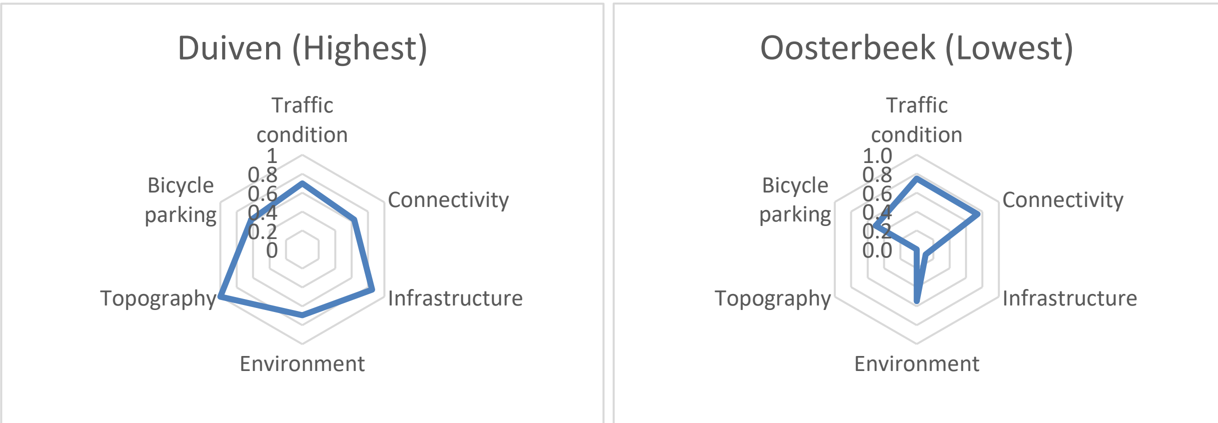

Figure 14. The radar chart of the highest and the lowest bikeability indexes

4.5. Analysis of criteria for stations with urban and suburban stations

This section explains the score of each criterion and compares the scores of 21 stations which classified as the urban station and suburban stations. The typology is based on the location the stations which can be seen on the map. The detailed comparison also shows Arnhem Centraal as the urban station and Duiven as the highest bikeability index of suburban stations. The purpose of this detailed comparison is to identify built environment and transport characteristics in the immediate surrounding area the urban and suburban stations, i.e., for the spatial scale of 800 meters.

4.5.1. Traffic condition

Based on the calculation, the traffic condition scores are better for higher spatial scales, probably because the urban centers tend to have more intersections than suburban areas. Figure 15 shows, for instance, that urban stations (such as 1 and 9) score low for 800 meters buffer and medium for 2400 buffers.

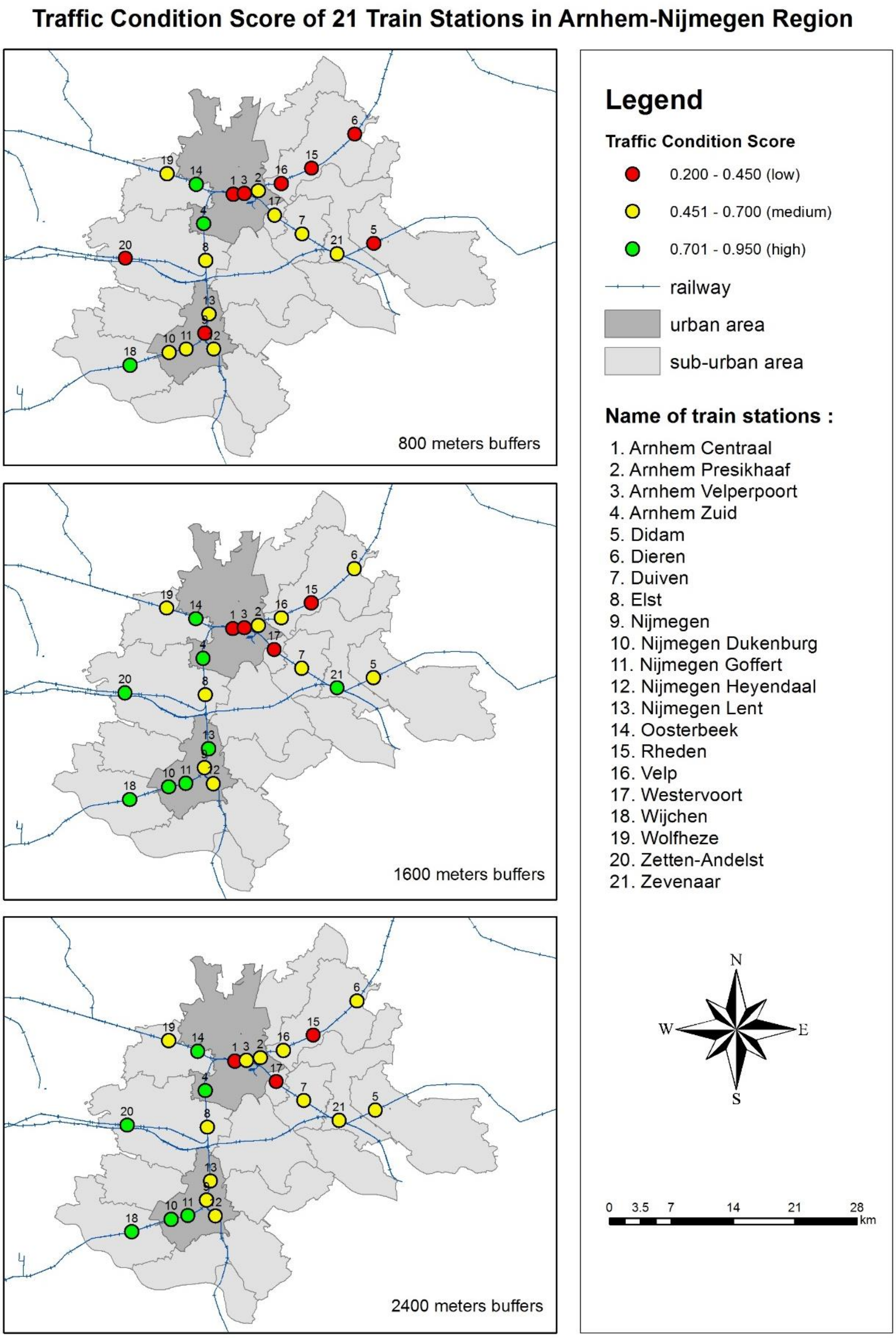

Figure 15. Traffic condition map

The next comparison is the traffic condition of Arnhem Centraal (urban) and Duiven (suburban). Figure 16 shows (two figures on the left) that traffic disruption is higher around the urban station area, illustrated by the higher amount of medium (yellow) or high (red) traffic disruption. As for the suburban station (left bottom figure), it shows more green segments, indicative of low traffic disruption. Besides that, the traffic condition criteria also evaluated the maximum speed of motorized traffic surrounding station areas. The same pattern as described above is observed: the urban station has higher occurrence of medium speed (50km/h, illustrated in yellow) than in the suburban area (30km/h, represented in green). Results are in line with expectations, as urban area tend to have more intersections and higher traffic volumes and speeds than suburban areas.

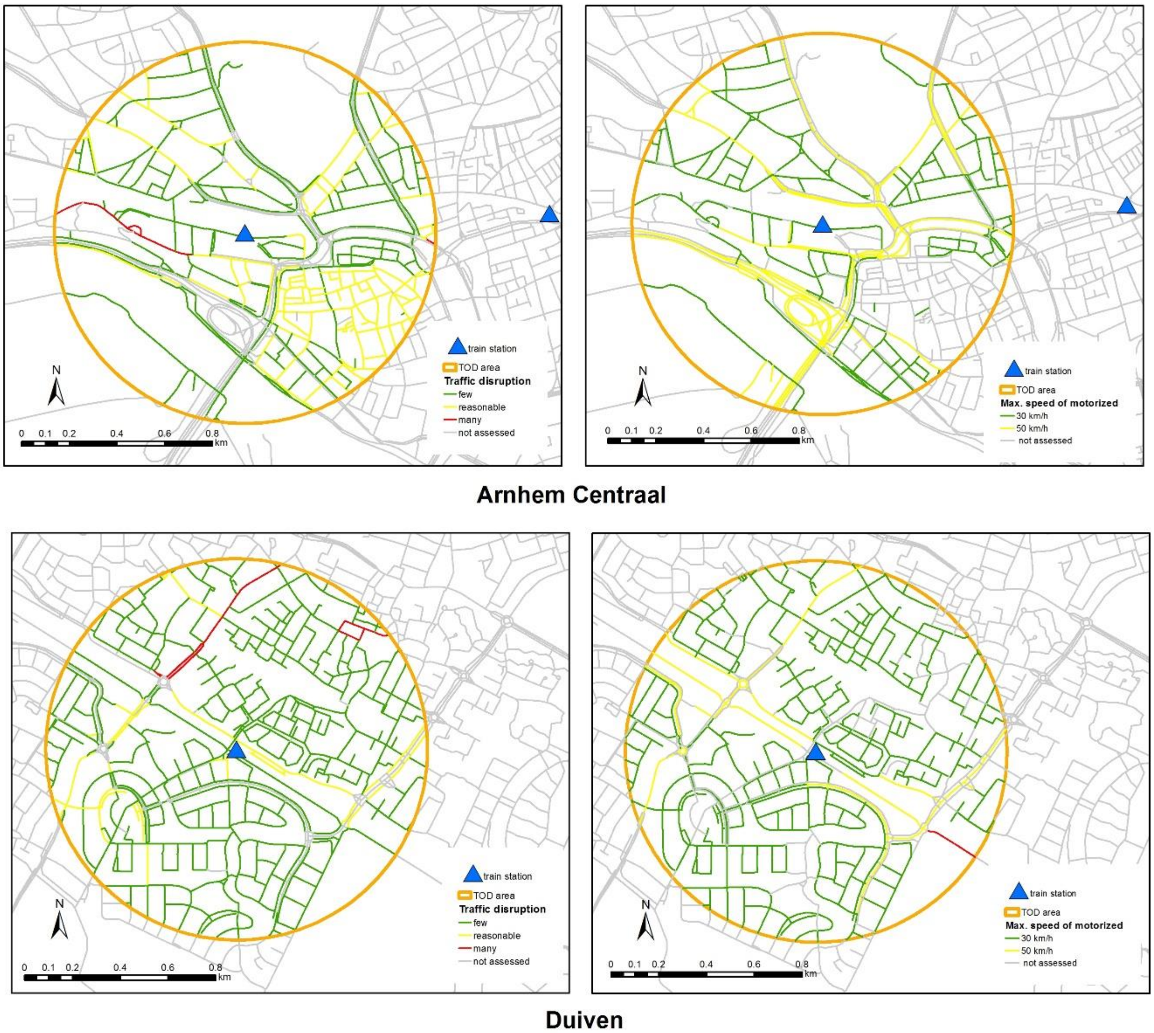

Figure 16. The comparison of traffic condition in urban and suburban station

Table 10. The measurement variables of traffic condition's indicators

Indicators	Arnhem Centraal (urban station)	Duiven (suburban station)
Traffic disruption (Low - green)	64.87%	85.81%
Traffic disruption (Medium- yellow)	32.56%	10.92%
Traffic disruption (High - red)	2.56%	3.28%
Maximum speed (Low - green)	53.54%	83.55%
Maximum speed (Medium- yellow)	46.46%	15.82%
Maximum speed (High - red)	0%	0.63%

4.5.2. Connectivity

On figure 17, it can be seen that the urban stations have the lower score of connectivity than the suburban stations. It probably because of in the urban area the density of the area is dense and more intersection which decrease the connectivity.

Figure 18 show the comparison connectivity map of Arnhem Centraal (left) and Duiven (right). As mentioned previously, this criterion is measured by four indicators which are the density of intersection with traffic lights, the density of intersection without traffic light, cycling route directness and bicycle lanes density.

The building in the urban is denser than in the suburban area. The density of the building impact to the connectivity. To connect each area the high number of bicycle lanes is needed, but its impacts to the number of intersection which decreases the connectivity. The high number intersection impact to the delay of the travels because the cyclist must reduce their speed in the intersection. The presence the busy road in the urban area also influence the connectivity. To cross those the road, the cyclists must add more time because of the traffic light delays. As visually, we can see that on figure 18 that the number intersection with traffic lights (red points) are more in urban area than in suburban. Also, table 11 show that no intersection with traffic lights in Duiven.

If we look in the urban, the bicycle lanes is dominated by two direction lanes (green segments). On the suburban, the lanes also dominated by the two directions but there are some significant number of one direction lanes (red segments). It can be concluded that the accessibility of the lanes influences the cycling route directness. The cyclists are easier to reach the stations if the lanes is dominated by two directions because they not must to pass the long route.

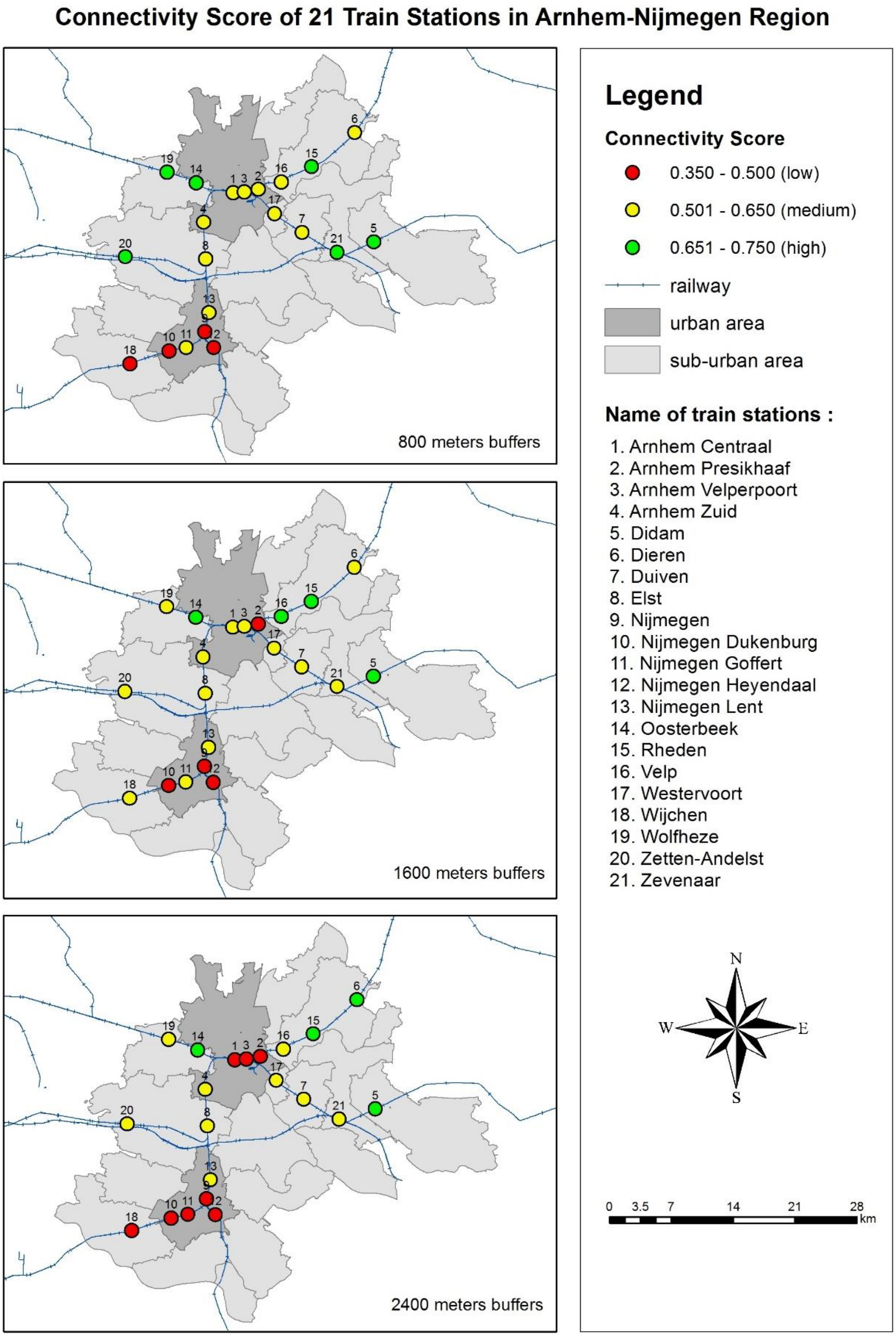

Figure 17. Connectivity map

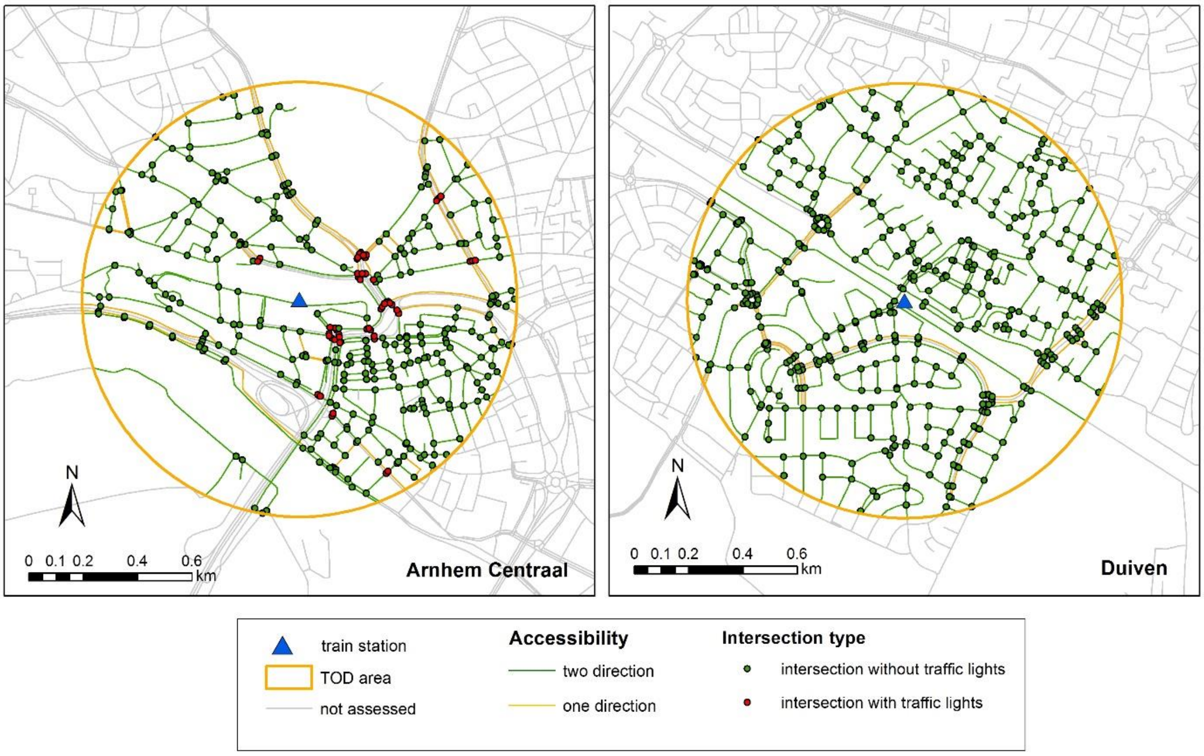

Figure 18. The comparison of connectivity in urban and suburban station

Table 11. The measurement variables of connectivity's indicators

Indicators	Arnhem Centraal (urban station)	Duiven (suburban station)
Intersection (Without traffic light - green)	85.09%	100%
Intersection (With traffic light - red)	14.91%	0%
Accessibility (Two direction - green)	79.53%	92.29%
Accessibility (One direction- red)	20.47%	12.90%

4.5.3. Infrastructure

As general, the infrastructure of surrounding the train stations in this area are feasible because only two stations that included the low score of infrastructure in all three spatial scales. It can be seen that the number of high scores are decreasing in higher spatial scales. It probably more segregation of cycling lanes infrastructure in the higher spatial scales.

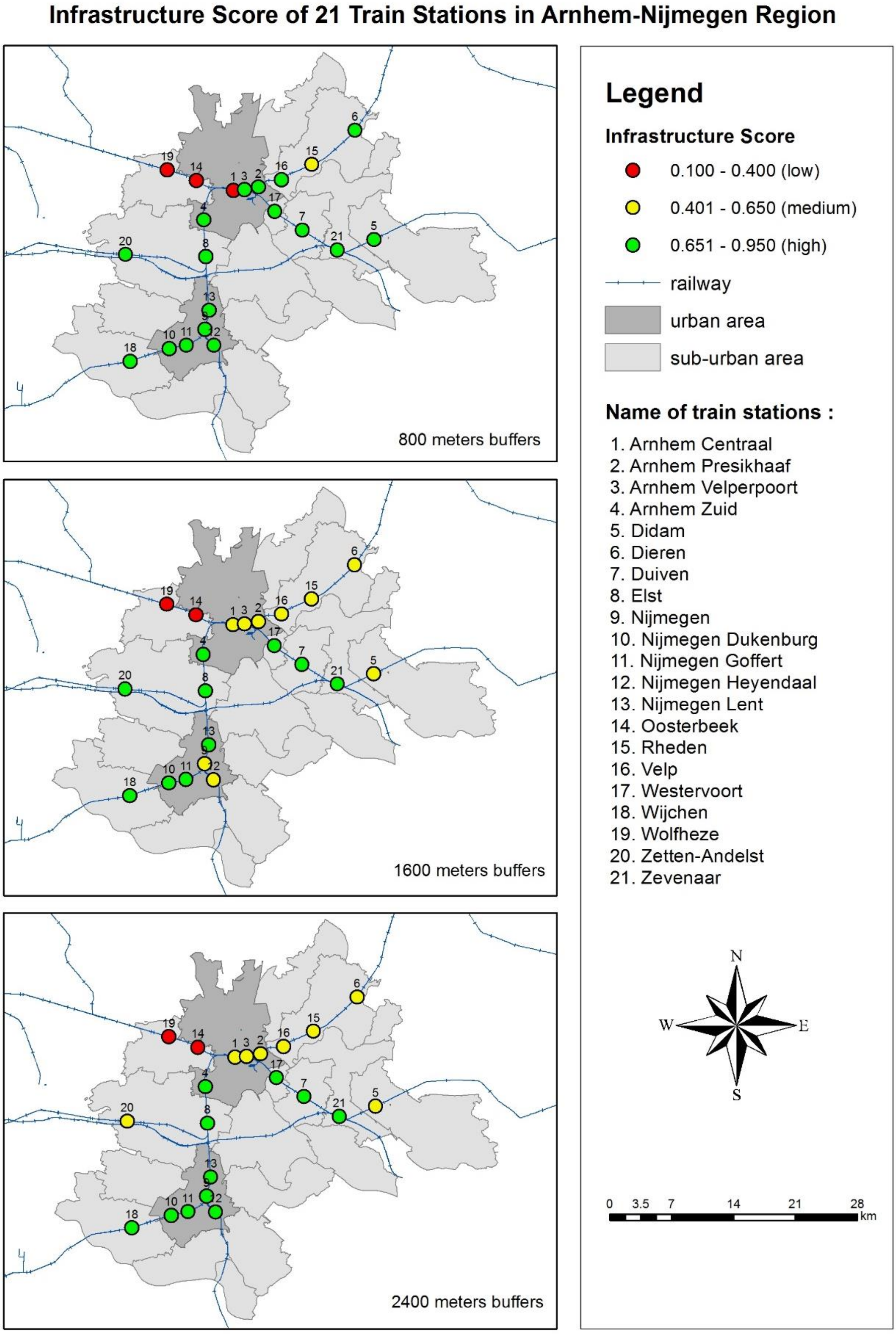

Figure 19. Infrastructure map

Figure 20 show the comparison the infrastructure's indicators of the Arnhem Centraal station as the urban station (top) and Duiven as the suburban station (bottom). Infrastructure is measured by three indicators: type of the road, quality of road pavement and quality of street lighting. The detail of the data is showed on table 12.

On the figure (left) it can be seen that both stations are dominated by normal road (yellow segments). However, the length of pedestrianized roads (red segments) are more in urban area than in suburban. This road type is the lowest level of score because the cyclists have limited accessibility. The presence of this pedestrianized road because the domination of commercial area in urban which need safety road for pedestrians.

Figure 20 (middle) shows that in the both stations, the lanes are dominated by good quality (green segments) and reasonable quality (yellow segments). However, in urban stations several bad quality exist (red segments). This criterion also evaluated by the street lighting which showed in figure 20 (right). Both stations are dominated by good lighting (green segments) although some lanes have no lighting (red segments) in urban area stations.

The results in line with the expectations that in the urban area, people tend to walk and use public transport than cycling. Therefore, infrastructure for the pedestrians has more attention than cyclists. For example, figure 19 shows that urban station (Arnhem Central) reached high scores in higher spatial scales. In contrast, in higher spatial scales, several suburban stations have low scores.

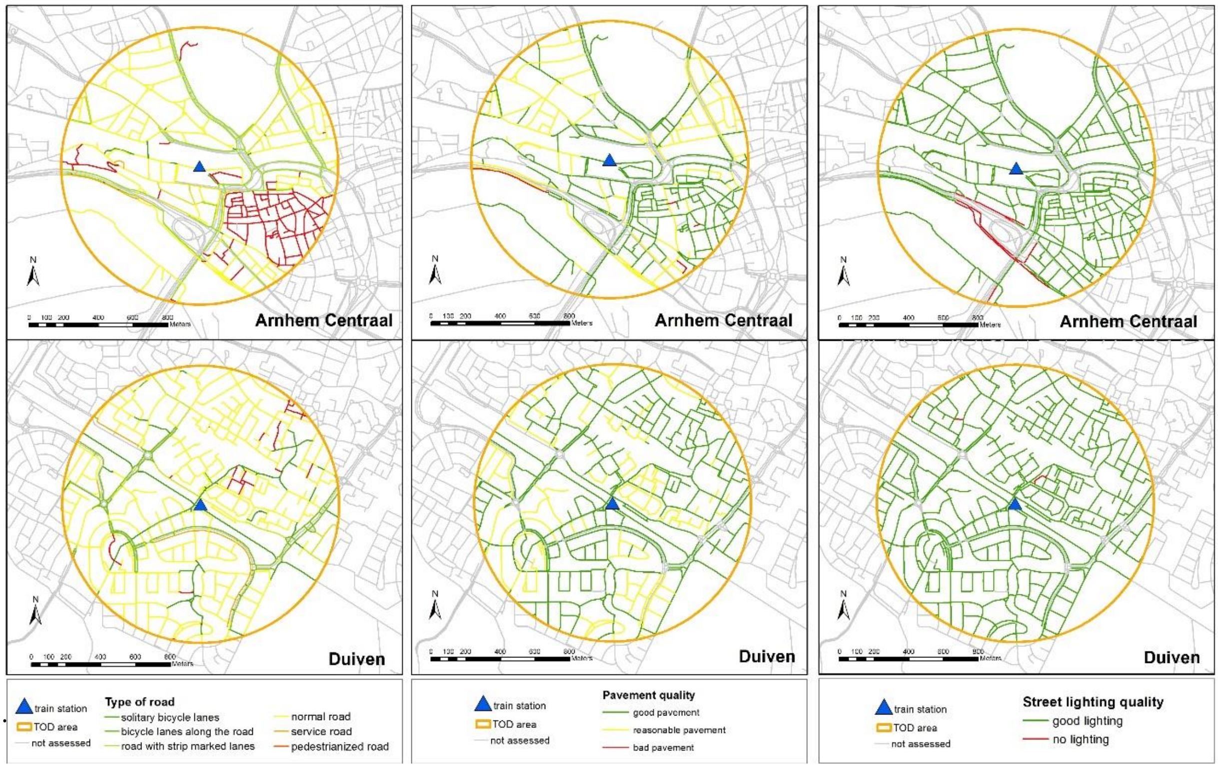

Figure 20. The comparison of infrastructure in urban and suburban station

Table 12. The measurement variables of infrastructure's indicators

Indicators	Arnhem Centraal (urban station)	Duiven (suburban station)
Type of road (Solitary lanes – dark green)	1.21%	8.56%
Type of road (Lanes along the road- green)	25.55%	15.74%
Type of road (Road with strip marked – light green)	7.45%	4.14%
Type of road (Normal road– yellow)	44.10%	64.60%
Type of road (Service road – orange)	1.60%	3.33%
Type of road (Pedestrianized road – red)	20.10%	3.62%
Pavement quality (Good - green)	60.67%	70.79%
Pavement quality (Reasonable - yellow)	37.61%	29.21%
Pavement quality (Bad - red)	1.72%	0%
Street lighting quality (Good lighting - green)	94.18%	99.55%
Street lighting quality (Limited lighting - yellow)	0%	0%
Street lighting quality (No lighting – red)	5.82%	0.45%

4.5.4. Environment

The environment of bicycle lanes is measured by how the beautiful, along with water area, built-up area and green area the lanes. In figure 21 shows that several urban stations have the low scores in higher spatial scales. In contrast, the suburban stations have high score in higher spatial scales. The supposition is the immediate area of urban stations are dominated by monumental building, water area (canals) and built-up area with little of green area. On the other hand, the higher spatial scales of suburban stations area dominated by the beautiful nature, water area and a lot of green areas.

Figure 22 shows the environment of Arnhem Centraal (left) which located in urban area and Duiven (right), the suburban station. The detail of the indicators can be seen on table 13.

The figure (top) shows that lanes with water area is not dominated in both stations area. However, table 13 shows that length of lanes along water area (green segments) in urban area is more than in suburban.

On the figure (middle top), it can be seen that both of stations area dominated by neutral area (yellow segments). However, the length of lanes with beautiful (green segments) in urban area station are more than in suburban. The stations in urban area tend to surround by monumental building or special architecture. In addition, the figure (middle bottom) shows that lanes in both station areas is also surrounded by the built-up area (green segments).

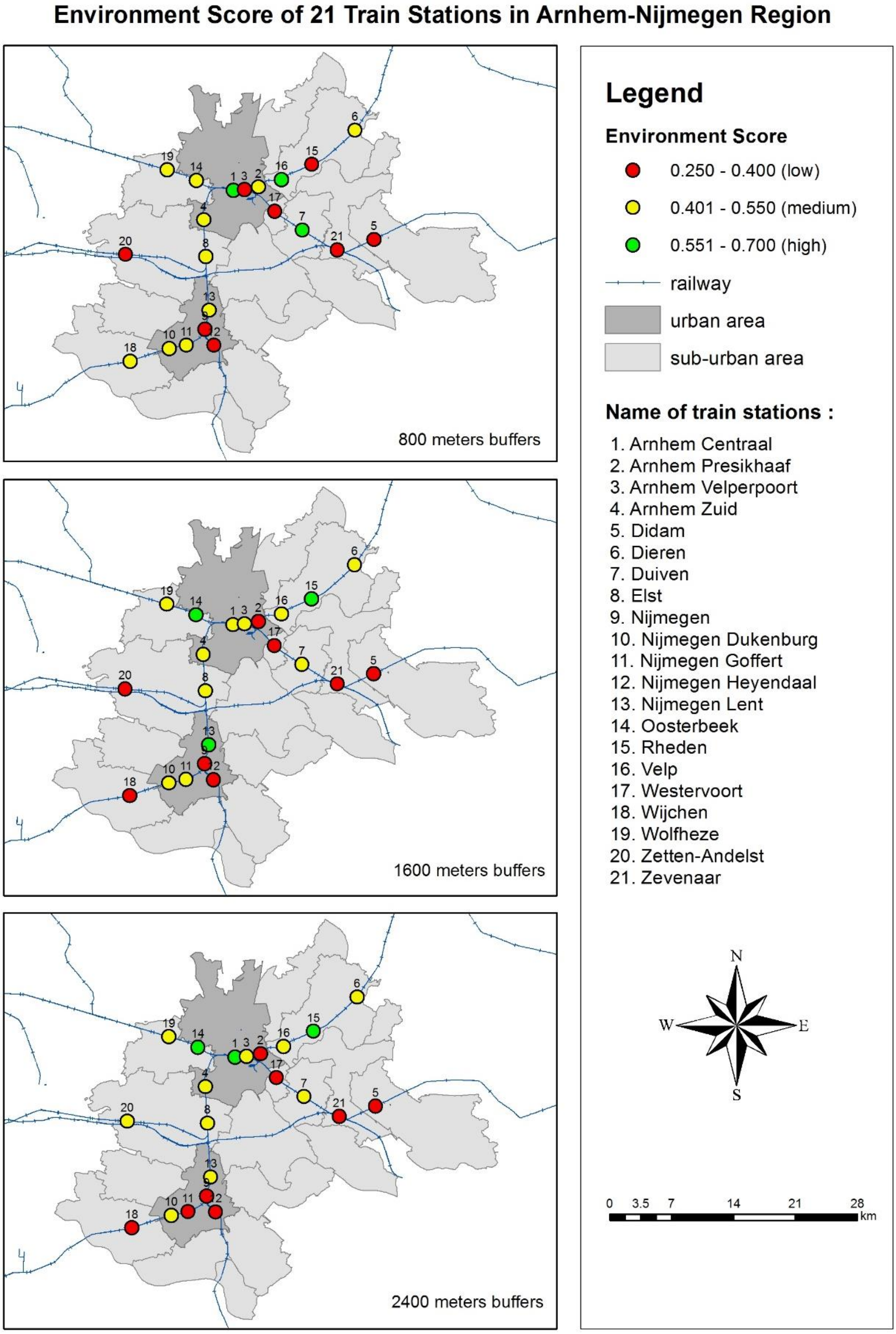

Figure 21. Environment map

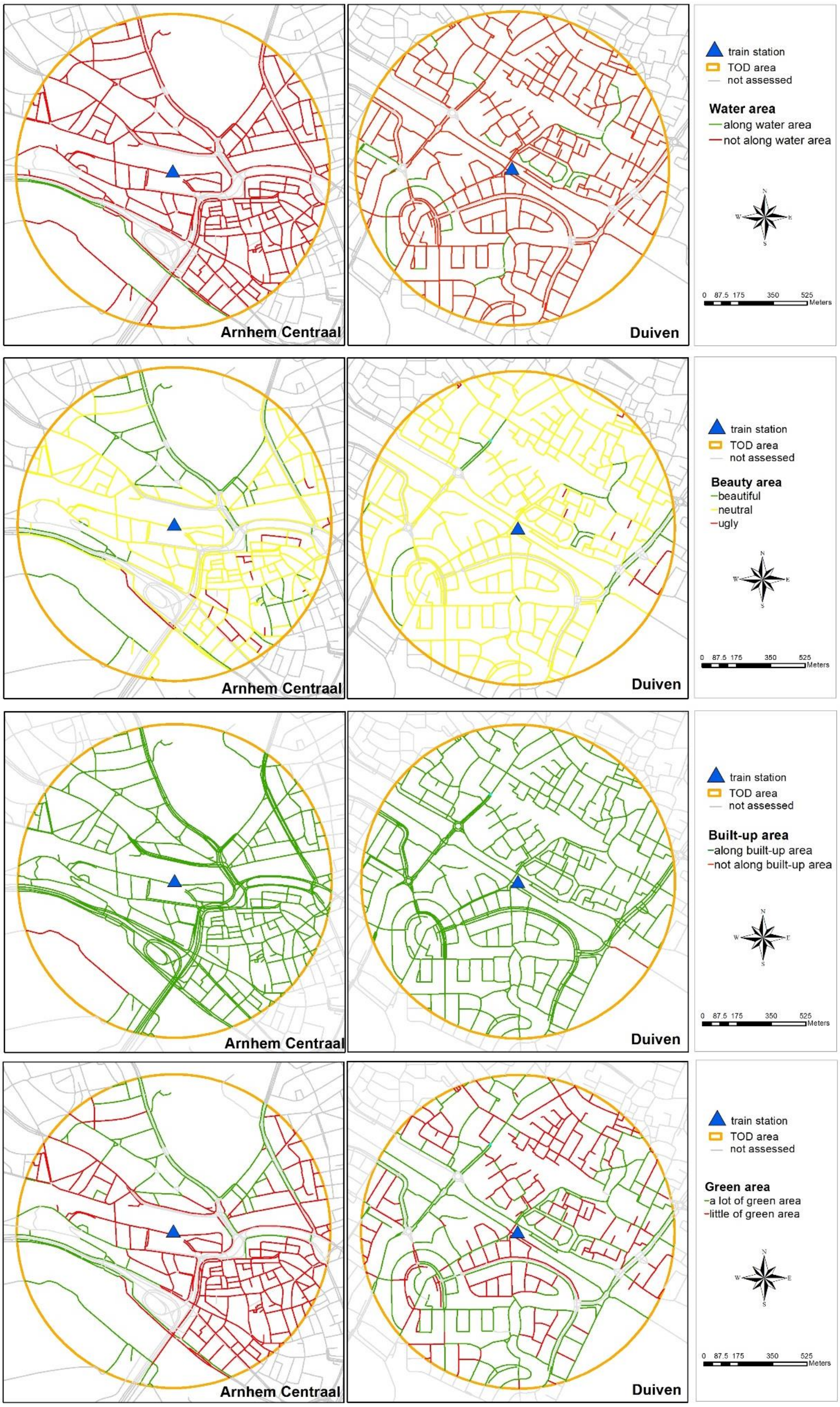

Figure 22. The comparison of environment in urban and suburban station

Table 13. The measurement variables of environment's indicators

Indicators	Arnhem Centraal (urban station)	Duiven (suburban station)
Water area (Along water area – green)	4.94%	8.85%
Water area (Not along water area - red)	95.06%	91.15%
Beauty area (Beautiful – green)	29.54%	8.24%
Beauty area (Neutral – yellow)	65.77%	89.72
Beauty area (Ugly – red)	4.69%	2.04%
Built-up area (Along built-up area – green)	96.86%	99.48%
Built-up area (Not along built-up area - red)	3.14%	0.52%
Green area (A lot of green - green)	37.62%	59.48%
Green area (Little of green - red)	62.38%	40.52%

4.5.5. Topography

On the maps (figure 23), it can be seen that only two stations which included as the low score of topography for three scales. It shows that as general the topography of TOD area in Arnhem-Nijmegen are flat and it support the cycling activities.

Unlike other criteria, topography is measured by one indicator which is the maximum percentage of the slope. Figure 24 shows Arnhem Centraal (left) as an urban station topography and Duiven (right) as the suburban. The detail can be seen on table 14. On the figure it can be seen that the bicycle lanes in Duiven are more flat than in Arnhem Centraal.

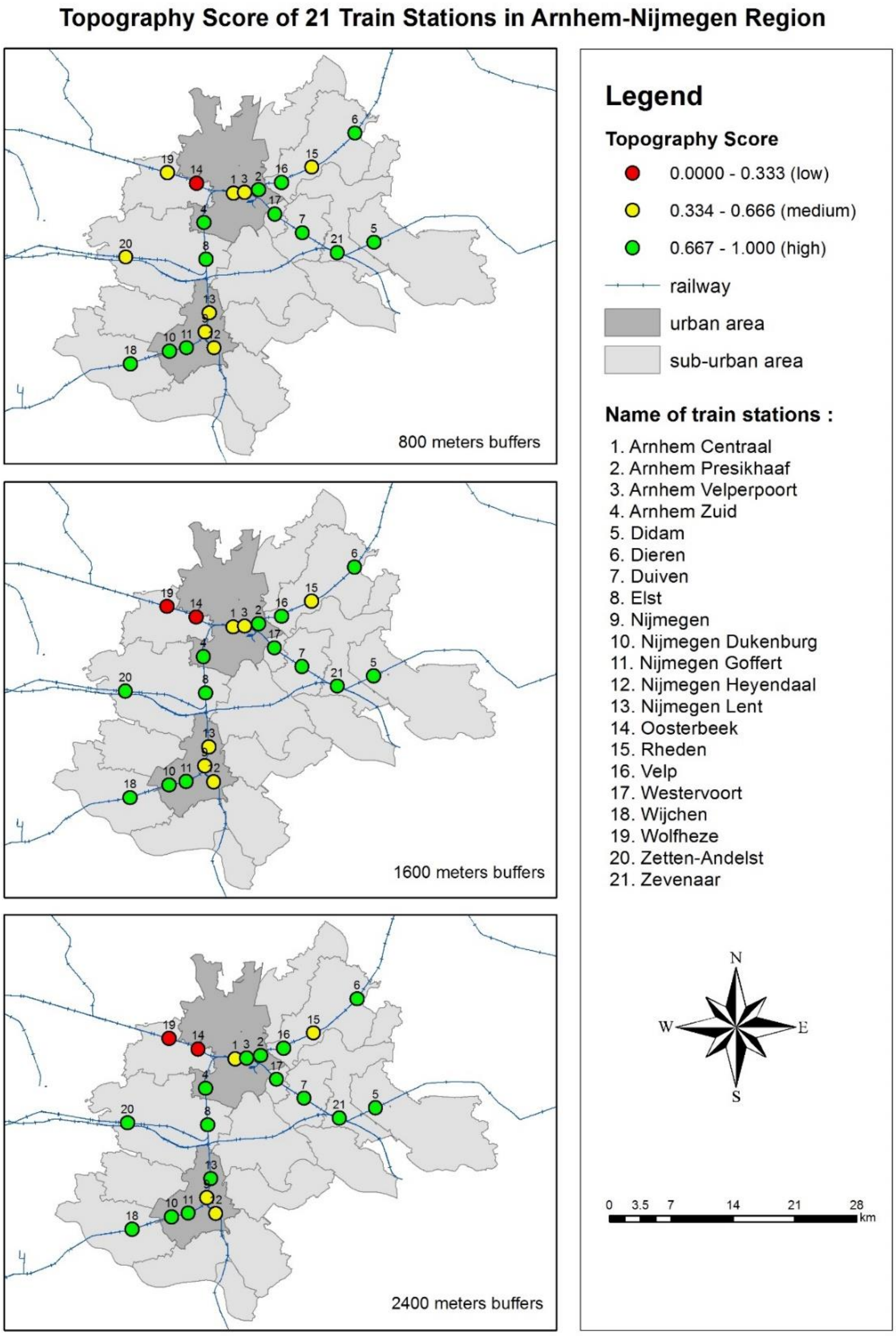

Figure 23. Topography map

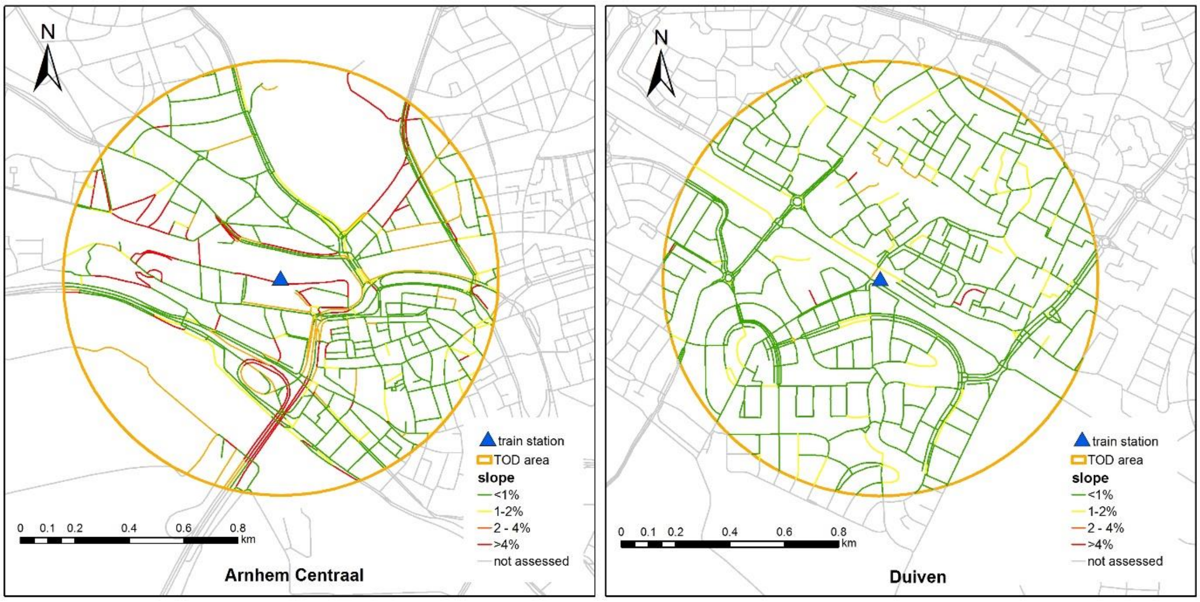

Figure 24. The comparison of topography in urban and suburban station

Table 14. The measurement variables of topography's indicators

Indicators	Arnhem Centraal (urban station)	Duiven (suburban station)
Slope (<1% – green)	63.42%	86.48%
Slope (1-2%- yellow)	9.37%	11.41%
Slope (2-4% – orange)	13.99%	1.44%
Slope (>4%– red)	13.22%	0.66%

4.6. Implication of bikeablity index on ridership

Table 10 shows the bikeability index compared to train frequencies and average daily passengers per day of each station. The hypothesis is that the surrounding areas of stations with high frequencies of trains and high number of the passengers would score high in bikeability, i.e., travellers would be able to travel to, and park their bicycles at the stations, prior to their train trip.

The region Arnhem-Nijmegen is served by four train providers: NS, Arriva, Hermes, and Veolia. Eight lines serve this region, as Figure 25 shows. The number of departure trains from the stations per day were counted based on the information provided at **http://www.ns.nl**. The calculation is based on workdays and do not include weekend and special days. In addition, the average daily number of passengers boarding each station was available at **http://www.treinreiziger.nl**. It was calculated based on a representative working day.

The train frequencies and average passengers per day were categorized into three classes: high (green), medium (yellow), and low (red), illustrated in table 15. Contrary to the prior expectations, both central stations (Arnhem Centraal and Nijmegen Centraal) have high train frequencies and high number of passengers boarding, but have low or medium bikeability index (depending on the spatial scale). On the contrary, a suburban station, such as Duiven, has a medium train frequency and low number of passengers boarding, but scores high in bikeability on all three spatial scales. The following analysis aims to reflect on such findings, and will explore how each bikeability criteria tends to perform in urban and suburban settings.

Table 15. Bikeability index analysed in relation to train frequencies and number of passengers per day per station

Station	Train frequencies per day	Average number of passengers per day (2014)	Bikeability Index (800m)	Bikeability Index (1600m)	Bikeability Index (2400m)
Arnhem Centraal	597	38442	0.543	0.571	0.609
Arnhem Presikhaaf	70	3022	0.668	0.556	0.528
Arnhem Velperpoort	128	2191	0.528	0.527	0.542
Arnhem Zuid	143	2925	0.718	0.720	0.708
Didam	128	1812	0.569	0.590	0.596
Dieren	140	3777	0.575	0.600	0.610
Duiven	128	3658	0.750	0.693	0.657
Elst	194	3763	0.694	0.688	0.686
Nijmegen	398	43149	0.548	0.558	0.614
Nijmegen Dukenberg	104	1922	0.666	0.654	0.661
Nijmegen Goffert	104	No Data	0.640	0.644	0.645
Nijmegen Heyendaal	76	3246	0.572	0.537	0.547
Nijmegen-Lent	143	1048	0.590	0.622	0.591
Oosterbeek	66	455	0.441	0.469	0.492
Rheden	70	838	0.532	0.551	0.561
Velp	70	1500	0.624	0.596	0.591
Westervoort	128	No Data	0.613	0.590	0.594
Wijchen	104	4045	0.687	0.703	0.693
Wolfheze	66	535	0.558	0.402	0.443
Zetten-Andelst	48	705	0.566	0.646	0.637
Zevenaar	128	4126	0.658	0.669	0.673

Bikeability Index
Low : 0.400 – 0.550
Medium : 0.551 – 0.650
High : 0.651 -0.750

Train Frequencies per day
Low : 0 – 100
Medium : 101 – 350
High : 351 - 600

Average number of passengers per day
Low : 0 – 15000
Medium : 15001 – 30000
High : 30001 - 45000

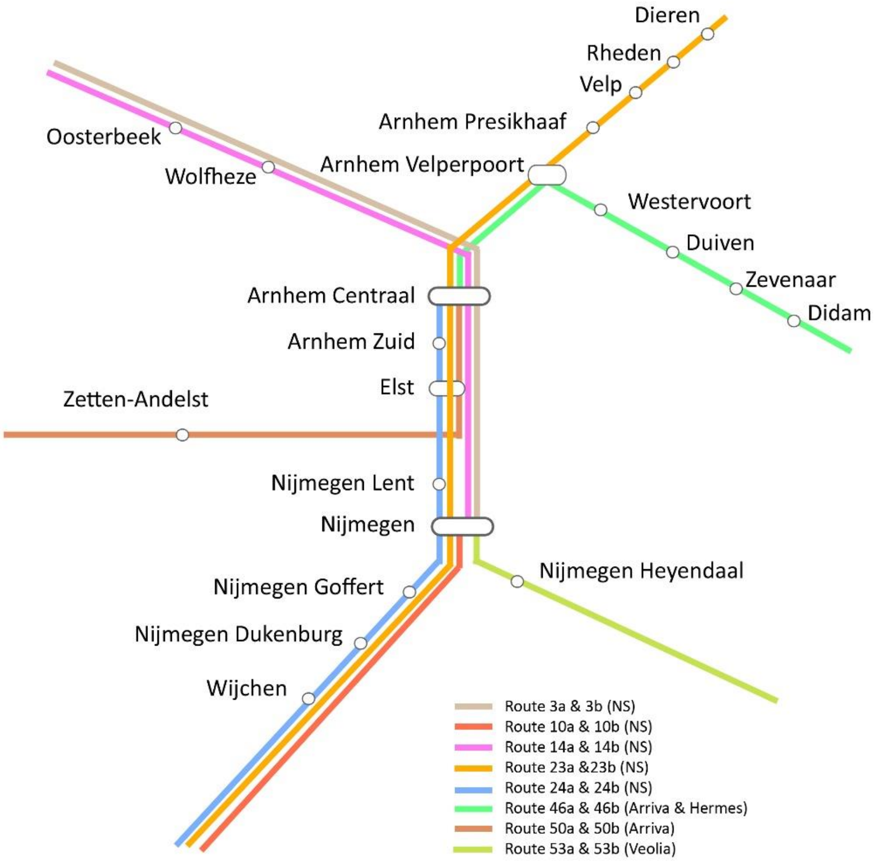

Figure 25. The train routes in Arnhem-Nijmegen region

Singh (2015) developed a TOD index to measure the TOD-ness on the same study area. The design aspect was measured combining walkable and cyclable infrastructures, and the results for stations Arnhem Centraal (urban station) and Duiven (suburban station) are illustrated on figure 26. Although the bikeability index here developed was based on different and a more extensive list of indicators, and serve a different purpose than the one from Singh, the comparison of results would allow understanding whether extending the list of indicators to measure bikeability would result in major or minor differences when compared to a more concise indicator.

Figure 25 shows TOD index results of stations Arnhem Centraal and Duiven as calculated by Singh (2015). Here the focus should be on the "Walkability and Cyclability" indicator only. The spatial scale used by Singh was also 800 meters. She found that station Arnhem Centraal scored around 0.70 whereas station Duiven scored around 0.90. The present research calculated bikeability scores of respectively 0.54 and 0.75. Although the difference is not substantial (around 0.15), it is interesting to confirm that on both studies urban stations tend to score lower on bikeability than suburban stations. This is an expected result, which will be reflected in light with the criteria that were selected by this study.

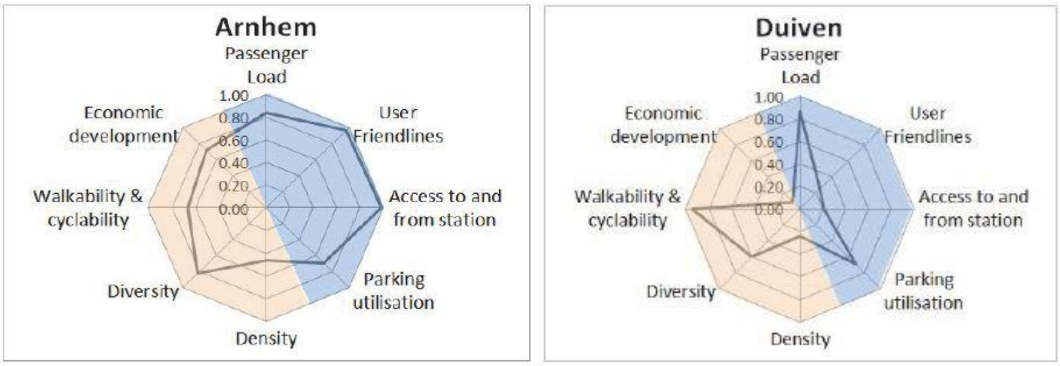

Figure 26. TOD index of Singh (2015)

Regarding **traffic conditions**, as well as **connectivity**, because urban areas tend to have more intersections, it imposes more traffic disruptions to cyclists and pedestrians to access a train station.Motorized transport in urban or suburban areas would not have substantial differences in the Netherlands, as usually the maximum speed around station areas is 30km/h.

As for the **infrastructure** aspects, suburban areas tend to have more segregation of cycling paths then urban areas, which contributes positively to the bikeability score. In addition, Dutch urban or suburban settings would not differ substantially regarding quality of the road pavement or street lightening. The **environment** criteria in potentially benefiting suburban landscapes as it was captured by how beautiful, green, along water canals or along built-up area cycling networks are placed.

Although **topography** was also acknowledged as important for measuring bikeability, in the Dutch context, it would not differ substantially for urban or suburban areas. As for **bicycle parking** conditions, urban areas tend to have higher capacity bicycle parking, with more services (such as 24 hours parking, guarded parking) than those found in stations in suburban areas. Figure 26 illustrate the bikeability scores for an urban and a suburban station, in relation to the six criteria here discussed.

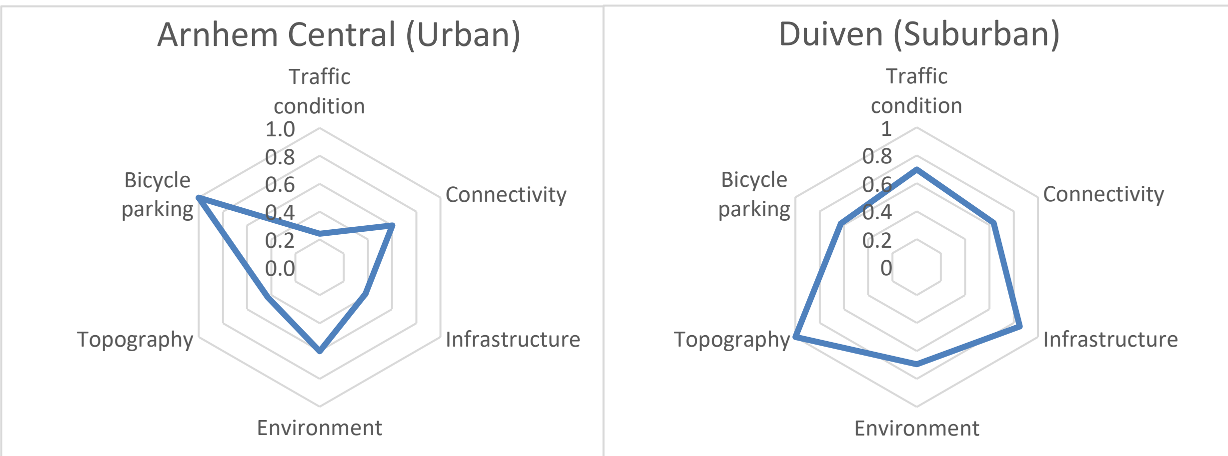

Figure 27 Urban versus Suburban bikeability scores

5. CONCLUSION

The aim of this study was to develop a bikeability index to assess TOD nodes in relation to the design aspect under the 5D approach (Cervero & Kockelman, 1997). This is specially relevant in the Dutch context, where bicycles are used as a feeder mode to higher speed and higher capacity public transport, such as train, forming a hybrid transport mode (Kager et al., 2016).

Relevant criteria and indicators to measure bikeability in general, and around TOD specifically were selected based on literature review. Six criteria were selected (traffic condition, connectivity, infrastructure, environment, and topography) and measured through several indicators. The Arnhem-Nijmegen TOD system, in the Netherlands, is composed by 21 train stations and was used as a case study. Three spatial scales were analysed: 800, 1600 and 2400 meters. No significant differences on the overall bikeability index were found. However, there are some significant differences on the criteria score.

Two typologies were used to analyse the 21 stations, leading to the analysis of differences on bikeability of urban and suburban areas. It was found that urban stations tend to score lower on bikeability than suburban station. Singh (2015) also found the same relation, which supports our results. However, although the bikeability index developed in this study were based on a more extensive list of indicators, and serve a different purpose than the one from Singh. The comparison of results would allow understanding whether extending the list of indicators to measure bikeability would result in major or minor differences when compared to a more concise indicator. The results for urban and suburban settings were discussed in light with the criteria selected by this study.

One may argue that developing an indicator specifically focused on measuring bikeability around a TOD environment is not "worth the effort", because the same relations were found with a more concise indicator, as the one used by Singh (2015). However, the bikeability index here developed provides a more detailed view on which factors affect cycling behaviour when the bicycle functions as a feeder mode to transit, which can only be captured with a more extensive list of indicators. This is especially relevant for policy makers when the interest is on strengthening the bikeability in urban or suburban areas.

This study has some limitations. The subjective measurement, such as along the beauty area, should be considered carefully in the indicators selection because the interpretation of subjective things is not the same one and another. In addition, the six criteria used for the measurement of the bikeability index are considered as having equal importance on bikeability, i.e., they have the same weight. However, depending on the contextual characteristics of a city/country, and also on individual preferences, some criteria may be valued more than others. For further research, a survey could be undertaken around each station area, or at least one representative urban and suburban station, where cyclists indicate the importance of each criteria when cycling towards a TOD node. The bikeability index would then be recalculated based on the new weighing scheme.

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APPENDICES

APPENDIX 1. The rank of bikeabilty index

Rank	800 meters		1600 meters		2400 meters	
	Name of stations	Index	Name of stations	Index	Name of stations	Index
1	Duiven	0.750	Arnhem Zuid	0.720	Arnhem Zuid	0.708
2	Arnhem Zuid	0.718	Wijchen	0.703	Wijchen	0.693
3	Elst	0.694	Duiven	0.693	Elst	0.686
4	Wijchen	0.687	Elst	0.688	Zevenaar	0.673
5	Arnhem Presikhaaf	0.668	Zevenaar	0.669	Nijmegen Dukenberg	0.661
6	Nijmegen Dukenberg	0.666	Nijmegen Dukenberg	0.654	Duiven	0.657
7	Zevenaar	0.658	Zetten-Andelst	0.646	Nijmegen Goffert	0.645
8	Nijmegen Goffert	0.640	Nijmegen Goffert	0.644	Zetten-Andelst	0.637
9	Velp	0.624	Nijmegen-Lent	0.622	Nijmegen	0.614
10	Westervoort	0.613	Dieren	0.600	Dieren	0.610
11	Nijmegen-Lent	0.590	Velp	0.596	Arnhem Centraal	0.609
12	Dieren	0.575	Didam	0.590	Didam	0.596
13	Nijmegen Heyendaal	0.572	Westervoort	0.590	Westervoort	0.594
14	Didam	0.569	Arnhem Centraal	0.571	Velp	0.591
15	Zetten-Andelst	0.566	Nijmegen	0.558	Nijmegen-Lent	0.591
16	Wolfheze	0.558	Arnhem Presikhaaf	0.556	Rheden	0.561
17	Nijmegen	0.548	Rheden	0.551	Nijmegen Heyendaal	0.547
18	Arnhem Centraal	0.543	Nijmegen Heyendaal	0.537	Arnhem Velperpoort	0.542
19	Rheden	0.532	Arnhem Velperpoort	0.527	Arnhem Presikhaaf	0.528
20	Arnhem Velperpoort	0.528	Oosterbeek	0.469	Oosterbeek	0.492
21	Oosterbeek	0.441	Wolfheze	0.402	Wolfheze	0.443

APPENDIX 2. Bikeability Index and Criteria Scores in Three Spatial Scales

Spatial scale : 800 meters

No.	Stations	Traffic condition score	Connectivity score	Infrastructure score	Environment score	Topography score	Bicycle parking score	Total Index
1	Arnhem Centraal	0.242	0.602	0.381	0.602	0.429	1.000	0.543
2	Arnhem Presikhaaf	0.605	0.549	0.880	0.435	0.912	0.625	0.668
3	Arnhem Velperpoort	0.392	0.531	0.737	0.299	0.581	0.625	0.528
4	Arnhem Zuid	0.878	0.646	0.863	0.440	0.858	0.625	0.718
5	Didam	0.384	0.676	0.674	0.239	0.816	0.625	0.569
6	Dieren	0.277	0.607	0.671	0.443	0.830	0.625	0.575
7	Duiven	0.698	0.633	0.850	0.695	1.000	0.625	0.750
8	Elst	0.629	0.563	0.931	0.502	0.917	0.625	0.694
9	Nijmegen	0.356	0.384	0.764	0.334	0.449	1.000	0.548
10	Nijmegen Dukenberg	0.694	0.455	0.891	0.457	0.876	0.625	0.666
11	Nijmegen Goffert	0.549	0.575	0.928	0.435	0.729	0.625	0.640
12	Nijmegen Heyendaal	0.649	0.466	0.877	0.350	0.467	0.625	0.572
13	Nijmegen-Lent	0.680	0.595	0.745	0.493	0.529	0.500	0.590
14	Oosterbeek	0.748	0.741	0.109	0.547	0.000	0.500	0.441
15	Rheden	0.372	0.707	0.581	0.260	0.644	0.625	0.532
16	Velp	0.416	0.627	0.700	0.555	0.823	0.625	0.624
17	Westervoort	0.474	0.622	0.749	0.363	0.844	0.625	0.613
18	Wijchen	0.800	0.496	0.939	0.404	0.859	0.625	0.687
19	Wolfheze	0.631	0.668	0.357	0.436	0.630	0.625	0.558
20	Zetten-Andelst	0.318	0.665	0.932	0.243	0.610	0.625	0.566
21	Zevenaar	0.547	0.686	0.752	0.379	0.959	0.625	0.658

Spatial scale : 1600 meters

No.	Stations	Traffic condition score	Connectivity score	Infrastructure score	Environment score	Topography score	Bicycle parking score	Total Index
1	Arnhem Centraal	0.380	0.501	0.549	0.489	0.504	1.000	0.571
2	Arnhem Presikhaaf	0.597	0.488	0.448	0.369	0.811	0.625	0.556
3	Arnhem Velperpoort	0.450	0.548	0.474	0.409	0.658	0.625	0.527
4	Arnhem Zuid	0.949	0.596	0.794	0.469	0.890	0.625	0.720
5	Didam	0.496	0.692	0.596	0.274	0.860	0.625	0.590
6	Dieren	0.507	0.650	0.529	0.476	0.813	0.625	0.600
7	Duiven	0.698	0.638	0.727	0.472	1.000	0.625	0.693
8	Elst	0.698	0.605	0.831	0.451	0.918	0.625	0.688
9	Nijmegen	0.485	0.377	0.587	0.345	0.554	1.000	0.558
10	Nijmegen Dukenberg	0.830	0.445	0.665	0.465	0.892	0.625	0.654
11	Nijmegen Goffert	0.757	0.513	0.722	0.477	0.772	0.625	0.644
12	Nijmegen Heyendaal	0.629	0.489	0.635	0.325	0.517	0.625	0.537
13	Nijmegen-Lent	0.781	0.540	0.696	0.612	0.604	0.500	0.622
14	Oosterbeek	0.847	0.750	0.158	0.558	0.000	0.500	0.469
15	Rheden	0.351	0.697	0.527	0.591	0.513	0.625	0.551
16	Velp	0.569	0.657	0.515	0.462	0.746	0.625	0.596
17	Westervoort	0.399	0.583	0.664	0.363	0.902	0.625	0.590
18	Wijchen	0.886	0.503	0.944	0.339	0.922	0.625	0.703
19	Wolfheze	0.539	0.648	0.135	0.413	0.053	0.625	0.402
20	Zetten-Andelst	0.732	0.643	0.656	0.370	0.853	0.625	0.646
21	Zevenaar	0.701	0.643	0.720	0.351	0.975	0.625	0.669

Spatial scale : 2400 meters

No.	Stations	Traffic condition score	Connectivity score	Infrastructure score	Environment score	Topography score	Bicycle parking score	Total Index
1	Arnhem Centraal	0.424	0.488	0.592	0.563	0.590	1.000	0.609
2	Arnhem Presikhaaf	0.479	0.442	0.503	0.327	0.795	0.625	0.528
3	Arnhem Velperpoort	0.454	0.498	0.538	0.428	0.711	0.625	0.542
4	Arnhem Zuid	0.859	0.599	0.812	0.488	0.863	0.625	0.708
5	Didam	0.471	0.682	0.606	0.316	0.878	0.625	0.596
6	Dieren	0.464	0.653	0.574	0.540	0.804	0.625	0.610
7	Duiven	0.536	0.640	0.720	0.439	0.982	0.625	0.657
8	Elst	0.613	0.613	0.872	0.498	0.896	0.625	0.686
9	Nijmegen	0.548	0.449	0.676	0.350	0.659	1.000	0.614
10	Nijmegen Dukenberg	0.834	0.408	0.766	0.416	0.915	0.625	0.661
11	Nijmegen Goffert	0.862	0.413	0.746	0.332	0.891	0.625	0.645
12	Nijmegen Heyendaal	0.599	0.456	0.677	0.371	0.553	0.625	0.547
13	Nijmegen-Lent	0.626	0.533	0.680	0.518	0.688	0.500	0.591
14	Oosterbeek	0.932	0.747	0.136	0.553	0.081	0.500	0.492
15	Rheden	0.341	0.729	0.599	0.654	0.419	0.625	0.561
16	Velp	0.565	0.596	0.572	0.457	0.731	0.625	0.591
17	Westervoort	0.405	0.545	0.655	0.365	0.968	0.625	0.594
18	Wijchen	0.905	0.465	0.862	0.322	0.979	0.625	0.693
19	Wolfheze	0.598	0.637	0.365	0.435	0.000	0.625	0.443
20	Zetten-Andelst	0.742	0.645	0.545	0.463	0.803	0.625	0.637
21	Zevenaar	0.694	0.617	0.751	0.349	1.000	0.625	0.673