# Developing a composite indicator for the 15-minute city concept based on accessibility measures and assessment of spatial inequalities of different socio-demographic groups

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## Abstract

The increasing population density in urban areas and concerns regarding sustainability and public health are cause for a need for more urban residents to adopt active mobility modes. Also, due to the covid-19 lockdowns and associated health concerns, people were motivated to adopt active modes rather than public transport. Lockdown restrictions brought to light transport inequalities particularly for the population groups relying on public transport, and already present underlying problems in spatial planning, with accessibility to some services low in certain areas. The 15-minute city - the idea of having basic needs and services within 15 minutes cycling or walking from one's home – aims to address issues concerning transport equality. It is argued that being in proximity of services can reduce car use, increase transport equity and traffic safety. However, there is limited research on the 15-minute city concept considering that the notion is relatively new and not comprehensively studied. Therefore, available methods and tools to measure a cities' progress towards becoming a 15-minute city are still missing. This research aims to develop a methodology for quantifying the 15-minute city through accessibility analysis. For this purpose, an x-minute city metric ($CS_x$) was developed and tested for cycling mode in a study area in the Netherlands. From the literature, nine different destination types were defined that are deemed important in the 15-minute city. Travel data from the Netherlands mobility panel (pre- and during covid) was analysed to determine input characteristics such as importance of destination types and distance decay functions. Standardized gravity-based 2-step floating catchment area (2SFCA) accessibility measures for all destination types were weighted and aggregated into a composite indicator that shows relative score as an x-minute city. The methodology was tested in a case study in the city of Utrecht, the Netherlands, and its surrounding suburbs. Results show that the city centre of Utrecht is largely a 15-minute city, as well as the centres of some of the surrounding suburbs. A 10-minute analysis was also conducted, showing that some areas do not have access to all services within 10 minutes cycling. Furthermore, some areas, such as the city centre, score higher as a 10-minute city than as a 15-minute city, but the areas right around the city centre as well as the edges of the suburbs benefit from a larger threshold travel time and score higher as a 15-minute city. Spatial regression on the 10-minute city score shows that population density, housing type, percentage of people with immigration background, and percentage children under 15 years old relate to the 10-minute city score. In a scenario analysis, new planned cycling connections were added in the network and assessed using the metric. Score improved in some areas as a result of the new connections but decreased in some places as a result of increased demand. Overall, the results show that some areas score much lower and might benefit from better cycling connections and/or more directed spatial planning of services. The developed indicator can be used to assess cities on their way towards becoming a 15-minute city, prioritise neighbourhoods to develop, set quantifiable goals, and evaluate planning scenarios.

*Keywords:* 15-minute city; accessibility; cycling; transport equity; spatial regression

## 1. Introduction

All around the world, urban population is increasing. The UN predicts that 61% of all people will be living in urban areas by 2030 (United Nations, 2018a). In cities, an increased population could cause problems such as overcrowded streets, increased traffic demand, and increased travel time to essential services. Road space has to be shared by more people causing more frequent traffic jams, coupled with polluted air and a diminished environment in cities. The ongoing Covid-19 pandemic and its lockdowns stalled some of these current problems such as traffic jams and polluted air in cities (Albayati et al., 2021; Van der Drift, 2021; Goenaga et al., 2021; Liu & Stern, 2021; Wang & Li, 2021). People travelled less, were more likely to stay close to home and choose active modes instead of a private car or public transit (Van der Drift et al., 2021). However, the lockdowns also exposed some weaknesses of current city planning; not all essential services can be found close to everyone's home, sidewalks are often too narrow for social distancing, and with public transit largely restricted or deemed unsafe, some locations can be hard to reach, especially for those without a car.

The 15-minute city, a concept first defined by Carlos Moreno in 2015 and discussed in more detail in Moreno et al. (2021), gained popularity during the pandemic because of this reason. The concept's goal is to give people access to all essential services and daily needs within 15 minutes of active transportation, thus reducing traffic demand, overall time spent in traffic, congestion, and pollution. Several cities around the world are now adjusting their transport policies to fit the 15-minute city concept, such as Paris, Barcelona, Melbourne, Portland, Shanghai, and more (Pozoukidou & Chatziyiannaki, 2021). Services that might be included within the 15-minute area for residents include public schools, parks, libraries, grocery stores and other retail, employment places, basic healthcare, and places for entertainment or recreation (Graells-Garrido et al., 2021; Moreno et al., 2021). Thus, a 15-minute city is one where, regardless of whether residents live in the city centre or in the suburbs of a metropolitan area, they can reach all their daily needs within 15 minutes from their home, without requiring a car. This not only calls for walkability and safe bicycle infrastructure, but also mixed land use, appropriate density, and an adequate spatial distribution of services, commerce, and green spaces. The April 2022 IPCC report states that to mitigate climate change, we should change current planning practices of cities and mentions the 15-minute city as a possible solution to reduce energy use in cities and reduce emissions (IPCC, 2022).

In the Netherlands, Utrecht is the first city that has stated they want to become a 10-minute city with services such as healthcare, sports, education, shopping, and more within a 10-minute walk or bike-ride from people's homes. Whether a city has ambitions to become a 10- or a 15-minute city, may have implications for requirements and necessary planning objectives. While some neighbourhoods in Dutch cities might already meet some of the requirements of 15-minute cities, these requirements have never been quantified, let alone measured. Population analysis from the UN has shown that also in the Netherlands the proportion of the population that lives in urban areas is still growing and has been growing steadily since the 1950s, much like in the rest of the world. Currently, 91.5% of the Dutch population lives in urban areas, and this is expected to increase to 94.8% by 2030 (United Nations, 2018b). The populations of the 4 largest cities in the Netherlands (Amsterdam, Den Haag, Rotterdam, Utrecht) are expected to grow with about 12% between 2015 and 2030 (CBS, 2016).

Current academic work on the 15-minute city has introduced the concept and defined it to some extent (Moreno et al., 2021), reviewed city plans for becoming a 15-minute city (Pozoukidou & Chatziyiannaki, 2021), and measured neighbourhood characteristics and travel behaviour (Carpio-Pinedo et al., 2021; Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021; Weng et al., 2019). Furthermore, some have measured potential for the 15-minute city with regards to walking mode (Abdelfattah et al., 2022; Caselli et al., 2022; Chabaud et al., 2022; Gaglione et al., 2022). However, an exploration of the concept in a Dutch setting where people are used to cycling has not yet been done. Some cities, including Utrecht in the Netherlands, have the ambition to become 15-minute cities, but relatively little is known about what the needs of different socio-demographic groups are, and to what extent those needs might already have been met. Furthermore, without first defining the concept and being able to measure the progress, it becomes hard to determine exactly what needs to be improved upon. A variation in which services are included exists as well, making it hard to compare different studies. A hard set of services included in every analysis makes it possible to benchmark different cities. Concerns regarding the 15-minute city arise in the form of possible gentrification and unaffordability of housing, and increasing inequality. Spatial inequalities and inequalities between socio-demographic groups in the 15-minute city have not been investigated yet.

Therefore, the aim of this research twofold: *develop a metric to assess 15-minute cities based on cycling accessibility measures, and assess whether Utrecht, the Netherlands and its surrounding towns are a 15-minute or*

*10-minute city*. Recorded travel data will be used to determine appropriate cycling distances and importance of different daily needs for people in urbanised areas in the Netherlands.

To fulfil the aim of the research the following sub questions will be answered:

1. What is a 15-minute city and which services should be present?
2. What mobility patterns can be derived from recorded travel data of different socio-demographic groups cycling in urbanised areas in the Netherlands?
3. To what extent do accessibility levels of different services in the study area establish the area as a 15-minute and a 10-minute city?
4. To what extent are socio-demographic and physical neighbourhood characteristics correlated with the metric and what are the spatial inequalities in the 10-minute city?
5. What is the effect of transportation measures on the metric?

As mentioned, while the concept of the 15-minute city considers both cycling and walking as transportation modes, this study only assesses the cycling mode.

The rest of this paper is structured as follows: section 2 presents the literature review, which introduces the definition of the 15-minute city concept and accessibility methods used in constructing the metric. Section 3 describes the study area and the data that was used in the study. Section 4 details the methodology. The results are presented in section 5, detailing first the accessibility results per destination type, and subsequently the 15- and 10-minute city results, as well as the results of spatial regression on the results (10-minutes) focusing on transport equity. Discussion and conclusion of the study are presented in section 6 and 7, respectively.

## 2. Literature review

Due to climate change, and transportation's substantial contribution to it, a behavioural shift is necessary. In the 15-minute city, opportunities are provided at close proximity, so that the shift to active transportation for everyone becomes easier, more natural, and more convenient.

The following sections expand on the 15-minute city concept and its definition, accessibility, and the research gap that this study aims to fill. An extended version of the literature review can be found in Appendix A.

### *2.1 The 15-minute city*

In a 15-minute city, residents should be able to access all of their essential needs within 15 minutes of travelling by active mode (walking or cycling), and thus the need for travel and specifically car travel will be reduced, and the goal of 15-minute cities is to retain local population locally (Graells-Garrido et al., 2021). The 15-minute city has been adapted to fit different regional needs, such as 20-minute neighbourhoods in Melbourne (Victoria State Government, 2017) and Portland (City of Portland, 2010), the 15-minute city in Paris (Paris en commun, 2020), and now the ambition of Utrecht for the 10-minute city (Gemeente Utrecht, 2021). Thus, despite the straightforward and quantitative nature of the name of the concept, there are many variations with different threshold travel times, and different modes included, such as public transit. Likewise, the types of services included that should be accessible within the specified travel time differ drastically between plans and in the literature (Carpio-Pinedo et al., 2021; Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021; Moreno et al., 2021; Pozoukidou & Chatziyiannaki, 2021; Weng et al., 2019).

Of course, the distance that can be covered by cycling for 15 minutes is different than the distance that can be covered by walking for 15 minutes. Therefore, the 15-minute travel time is not rigid and can be adjusted in different cases or contexts. Additionally, because of this discrepancy between cyclists and pedestrians, proximity indicators might be defined differently for cyclists than for pedestrians (Moreno et al., 2021). The Congress for New Urbanism (CNU) has defined different sheds within the 15-minute city for 5-minute walks, 15-minute walks, 5-minute bike rides, and 15-minute bike rides. According to the CNU, a radius of 0.4 km (5 minutes walking) is the size of a neighbourhood and should contain services essential for daily needs such as groceries. A radius of between 1.2 km (15 minutes walking) and 1.6 km (5 minutes cycling) is defined as an appropriate size of the 15-minute shed, labelled the 'range of the 15-minute city'. Within this area the most essential services should be located such as schools, parks, and commerce. Outside of this area, within a 4.8 km radius (15 minutes cycling), larger companies and employment centres, cultural institutions, entertainment services, higher education opportunities, large parks, and major medical facilities should be located (Duany & Steuteville, 2021).

Thus, multiple neighbourhoods that can be covered by a 5-minute walk are present within a 15-minute city (15-minute walk or 5-minute bike ride). CNU seems to be the only organisation that has quantified any characteristics of the 15-minute city so far, providing some requirements that cities can work towards in their planning. Definitions of the 15-minute city differ across countries, and there are variations when it comes to services or modes of transport included. Thus, it is not a one-size-fits-all concept, but the goal is the same: reduce traffic. It is also impossible to provide the same level of service and proximity to all inhabitants. Therefore, a definition considering 90% of inhabitants being able to reach their daily needs within 15 minutes is warranted (Moreno et al., 2021).

Cycling in the Netherlands is considered by many people as a main form of transportation. 28% of all trips in the Netherlands are by bicycle (CBS & RWS, 2020), more than other countries in Europe (Buehler & Pucher, 2012). Many trips already take place close to home, and people will generally choose their bike over walking if something is a bit further away. Therefore, the concept of 15-minutes cities in the Dutch context becomes slightly different. Cycling is a more frequently chosen alternative to driving than walking, because of good bicycle infrastructure, convenience, and a greater distance can be covered in a shorter amount of time by biking than by walking. People are quick to choose the bike when a destination is slightly too far to walk to, and arguably cycling is a more important mode of transport in the Netherlands than walking because of its convenience and greater range. Furthermore, people with disabilities are often able to ride an adjusted bike or other form of transport allowed on the bike path, although bike paths are not always accessible for these types of bikes (Fietsersbond, 2021). Not only is walking in the Netherlands not as important an alternative to driving as cycling but including walking in analysis requires a lot of data on infrastructure quality to accurately assess walkability. Thus, walking will not be taken into account as a mode in this study, and the research will focus on cycling and cycling accessibility.

It is worth noting that public transport should not be included as one of the modes used to define the 15-minute city because travel times on public transit depend on too many variables, such as delays and first- and last leg (Duany & Steuteville, 2021). Furthermore, 15 minutes is a relatively short amount of time. However, *access* to public transit hubs and stops is essential, for people unable to walk or bike, or to get out of the city every now and then.

### *2.1.1 Services in the 15-minute city*

Within the 15-minute city, a number of different services should be located. Moreno et al. (2021) state that six main categories should be present: living, working, commerce, healthcare, education, and entertainment. In their analysis of Barcelona, Graells-Garrido et al. (2021) also consider access to healthy food, government facilities, green spaces, and public transit. While healthy food might be considered within the commerce category of Moreno, it may be beneficial to regard it separately, because access to healthy food has an influence on overall health. Food deserts are places where access to grocery stores is low, either because of boundaries such as busy roads or highways, distance, or affordability (Shaw, 2006). Although, a study in Amsterdam showed that there were no real food deserts (Helbich et al., 2017), access to healthy and affordable food is important to consider in order to promote a healthy lifestyle compliant with the 15-minute city available to everyone. Furthermore, green spaces are an important asset in cities considering the effects of climate change and urban heat islands. While green spaces might be considered under the entertainment category, Moreno does not specifically state this.

Table 1 presents the services considered by papers that either define the 15-minute city concept or use it in analysis or assessment. The six main categories from Moreno seem to be present in some way in most of the other articles. The *living* category is captured by the origin points and spatial unit used in analysis, and the housing affordability category in Pozoukidou & Chatziyiannaki (2021). The *working* category is considered in Carpio-Pinedo et al. (2021) and Pozoukidou & Chatziyiannaki (2021) but no distinction is made between different types of jobs, or different types of workers. Gaxiola-Beltrán et al. (2021) include employment centres and make distinction in size (number of job positions). Employment is an important characteristic of the 15-minute city because most people travel to work each day. For proper analysis of job accessibility, distinction between job types and education levels of workers can greatly influence results (Cervero et al., 1995; Geurs & Van Eck, 2003; Shen, 1998), and competition effects should be included (Geurs & van Wee, 2004). Furthermore, commuting trips still predominantly take place in the car in the Netherlands: in 2019, 50% of all trips to and from work were by car, and 26% by bike, and the average trip distance to and from work is 9.72 km (CBS & RWS, 2020). Many people have to travel further than what is considered a bikeable distance to work. Moreover, the commute to work is a trip that recurs daily for many people and thus determines a large part of their mobility pattern. However, in the 15-minute city, work should be accessible within 15 minutes of cycling or walking as well. It is therefore important to include work destinations in analysis.

The *commerce* category is included in all other articles, but in different ways. (Gaxiola-Beltrán et al. (2021) only include supermarkets, which provide the most essential of daily needs. On the other hand, the other articles do not make distinctions between different types of commerce and do not analyse supermarkets separately. Graells-Garrido et al. (2021) consider supermarkets in their retail category together with other shops and malls. *Health* is also considered in all of the other articles. While some consider several types of healthcare, others consider all healthcare grouped and do not distinguish between types such as hospital, pharmacy, or general practitioner. However, these different health providers all have different amounts of people they need to service, and it is safe to assume that not every 15-minute neighbourhood needs regional services such as a hospital.

The *education* category is considered in 3 of the other articles. Gaxiola-Beltrán et al. (2021) and Weng et al. (2019) both distinguish different types and levels of education in their analysis, while Graells-Garrido et al. (2021) group all types together. Again, distinct types of schools have different catchment areas, and the presence of both an elementary school and high school in one neighbourhood provides more options for different types of families. Finally, there are some very distinctly different services included in the *entertainment* category in all articles. Gaxiola-Beltrán et al. (2021) do not consider entertainment at all, while in other articles a distinction is made between entertainment and recreation Graells-Garrido et al. (2021). Carpio-Pinedo et al. (2021) and Weng et al. (2019) include parks, sports venues, cultural venues, restaurants, entertainment venues, and leisure and hospitality types in their analysis that may all be considered part of the *entertainment* category.

***Table 1:*** *Services in academic literature on 15-minute cities*

| Source | Services | Use |
|---|---|---|
| Moreno et al. (2021) | Categories: Living, Working, Commerce, Healthcare, Education, Entertainment | Definition |
| Weng et al. (2019) | Services: Education (School or Training institution), Medical care (Hospital or Pharmacy), Municipal administration (Public transport; Park and square; Sports venue; Cultural venue), Finance and telecommunication (finance and post office), Commercial service (restaurant, shopping, entertainment venue), Elderly care (nursing home or elderly education) | Measuring walkable neighbourhoods |
| Pozoukidou & Chatziyiannaki (2021) | Categories: Work, Basic healthcare, Cultural and recreational opportunities, “key resources” | Assessing/evaluating transportation plans |
| Carpio-Pinedo et al. (2021) | Land-use types: Industrial, Offices, Commercial, Sports, Show business, Leisure and hospitality, Health, Cultural, Religious | Measuring walkability |
| Gaxiola-Beltrán et al. (2021) | Services: Schools (Preschool, Primary school, Secondary school, Technical secondary school, High school), Hospitals (General hospital, Addiction and psychiatric hospitals, other hospitals), Other (Supermarkets and Employment centres) | Assessing urban accessibility (walking and cycling) |
| Graells-Garrido et al. (2021) | Categories: Education, Entertainment, Finance, Food, Government, Health, Professional, Recreation, Religion, Retail, Public transport | Measuring 15-minute accessibility (walking) |

Through analysing travel behaviour and accessibility analysis, 15-minute cities have been measured before (Carpio-Pinedo et al., 2021; Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021). Graells-Garrido et al. (2021) analysed movement in and between neighbourhoods in the metropolitan area of Barcelona and discovered that people tend to travel to other neighbourhoods for services like retail and education. However, they were unable to account for bias in socio-economic and demographic groups because anonymised cell phone data was used. Gaxiola-Beltrán et al. (2021) assessed accessibility to essential services in the mega-city Monterrey using active modes and found that the district they analysed does not meet the requirements of a 15-minute city yet, because not everyone can reach schools or healthcare within a 15-minute walk. Finally, Carpio-Pinedo et al. (2021) measured the potential for walkable trips through looking at land use mix. If land use is mixed, origins and destinations appear at walking distances. The analysis concerned the metropolitan area of Madrid (including suburbs) and was based on individual building level spatial data.

### 2.1.2 *Four dimensions of the 15-minute city*

Moreno et al. (2021) define four dimensions for the 15-minute city: *density*, *proximity*, *diversity*, and *digitalization*. Density should be adequate to reduce sprawl and simultaneously promote proximity of services. However, too high density may lead to centralised development. The CNU defined several thresholds for residential density in their different sheds. The first shed of 5 minutes walking should contain about 2600 residents (around 5000/km2), and the 15-minute walking shed should contain around 23,500 residents (Duany & Steuteville, 2021). Diversity is applied two ways; diversity in land use in order to create mixed-use neighbourhoods, and diversity in culture and people. Mixed land use promotes walkability and proximity, while a multicultural society is beneficial for the economy and attractive for visitors. Diversity at the building level – multiple functions such as commerce and residential in one building – is important for optimal benefits and interaction. Finally, digitalization increases not only safety through e.g., sensors in traffic, but also efficiency of shopping, bike sharing facilities, and opportunities to work from home or any other location.

Accessibility (to services) is facilitated both through land use and transportation facilities, together with personal capabilities (Geurs & van Wee, 2004). However, considering the dimensions and distances that can be covered within 15 minutes of active transport, proximity to services is especially important to increase accessibility in the 15-minute city. Pozoukidou & Chatziyiannaki (2021) also argue for a shift in planning from accessibility of a neighbourhood in the context of the entire metropolitan region to planning for proximity of urban services within neighbourhoods. Thus, activities are brought to neighbourhoods instead of bringing people to the activities. Because of this, land use mix and (optimal) density are some of the key features of a 15-minute city. Furthermore, proximity to services has also been found to have a negative relationship with private car use in Melbourne (Boulange et al., 2017), meaning people are less likely to choose a private car if proximity increases.

Diversity could lead to more vibrant and connected communities. Mixed-use developments can address market demand for housing in an economically viable way and create sustainable spatial solutions (Delisle & Grissom, 2013), some of the key principles of the 15-minute city. Furthermore, together with density and pedestrian-oriented design, diversity may positively influence travel behaviour (Cervero & Kockelman, 1997). A diverse set of services in a single neighbourhood ensures that less traveling is necessary to reach all daily needs and makes for a more vibrant neighbourhood. A multicultural neighbourhood could promote tourism because of a more attractive environment to visitors, and ultimately create more job opportunities for locals and boost the economy.

A 15-minute city might, through its dimensions such as proximity and diversity, create more lively and liveable neighbourhoods. Additionally, some other hypothesized benefits include economic boost of the area, more social cohesion and interaction, more sustainability (Moreno et al., 2021), and health benefits for the population due to an increase in active mode share (Weng et al., 2019). Furthermore, higher walkability, more density and mixed land-use all contribute to increased walking and cycling and reduced car traffic (Adhikari et al., 2020; Boulange et al., 2017; Forsyth et al., 2007; Gao et al., 2020; Lee & Moudon, 2004; Riggs & Sethi, 2020; Saelens & Handy, 2008; Saelens et al., 2003). Other potential long term benefits of the 15-minute city may include an overall higher quality of life due to less time spent in traffic and better health, a higher cultural output, and bridging social inequality in accessing services (Moreno et al., 2021). Furthermore, in a 15-minute city, resilience against threats such as covid-19 may be higher. A more tightly knit social network means people are more likely to have a support system if they get ill or cannot leave their house. In addition to this, proximity of essential services means that public transport might not be necessary to fulfil daily needs. If job allocation and residents' location match better, essential workers are also able to independently arrive at their work – by bike or on foot.

## 2.2 *Accessibility measures for active transportation*

Many different methods for measuring accessibility by active transportation exist. Like other accessibility measures, they can be categorized into 4 groups; distance-based, gravity-based, infrastructure-based, and Walk Score types which consider multiple dimensions and are more like a composite measure of walkability or cyclability (Vale et al., 2016). In distance-based measures, only the travel time or distance from an origin to destinations is considered and either the destinations within a certain threshold are counted, the closest destination(s), or the mean distance or travel time to the closest opportunities. These accessibility measures require origin points, places of interest, and a network data set that includes pedestrian and cycle paths and are relatively simple to compute. However, the distance threshold is arbitrarily chosen and may have a large influence on the number of opportunities that can be reached. Apparicio et al. (2008), Mavoa et al. (2012), and Yigitcanlar et al. (2007) use multiple thresholds in order to (somewhat) combat this problem. Methods for calculating distance vary from Euclidian or Manhattan distance to network distances. Apparicio et al. (2008) found that results from Euclidian and Manhattan distance correlate highly with results generated by using network distance. However, network distance is a more accurate measure, and current technology and available data allows for relatively simple implementation.

Gravity-based measures assign weights to opportunities based on their distance or travel time from the origin point, and possibly other factors such as floor space (Sun et al., 2012) or number of employees (Kockelman, 1997; Manaugh & El-Geneidy, 2012). These measures are more realistic because destinations further away are less attractive than ones closer. Furthermore, they do not have the problem of the arbitrarily chosen distance threshold but do require more computation and historical travel data to fit a decay or impedance function needed for calculating the accessibility.

Two-step Floating Catchment area (W. Luo & Wang, 2003) is a combination of two accessibility measures that takes into account the supply and demand of a service. It is often used to measure accessibility to healthcare (GP) or other service providers with capacity constraints. The measure can be cumulative and based on floating catchment areas, where a maximum travel time is set. Otherwise, the measure can be adapted to be gravity-based, using a cost-function. The measure may be interpreted as the ratio of supply of a service to demand of the population.

Infrastructure-based accessibility measures do not take into account origins and destinations or opportunities in the area, but only consider the network itself. Characteristics such as type of cycle path, quality, sidewalk dimensions, and safety can be used to score the network. Many studies also use topology of the network such as connectivity, which is adequate to capture things in the network that could form an obstacle to pedestrians and cyclists, such as large roads that have to be crossed. However, this measure is not appropriate for the 15-minute city because travel time is not considered, while that is one of the main dimensions in the 15-minute city.

Lastly, some composite measures such as and its cyclability measure Bike Score (Winters et al., 2013), which is based on Walk Score (Walk Score, 2010), have been developed to capture both network qualities like the infrastructure-based measures, and travel time to opportunities much like the distance- or gravity-based measures. Bike Score uses a gravity-based approach and combines this with topological characteristics like connectivity and other aspects such as bike lane presence, hills, and destinations (Winters et al., 2013).

### *2.3 Research gap and contributions*

Currently, the concept of a 15-minute city has been qualitatively defined in Moreno et al. (2021) and interpreted in other studies (Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021; Pozoukidou & Chatziyiannaki, 2021). (Abdelfattah et al., 2022) used Walk Score and density to map the potential for 15-minute city in Milan, and (Gaglione et al., 2022) carried out an analysis for walking destinations to health centres and grocery stores in different districts in Naples. Accessibility analysis in (Chabaud et al., 2022) to different urban services was focused on walking as well, and labelled Barcelona as a 15-minute city. (Caselli et al, 2022) also investigate walkability to different services in a single neighbourhood. Thus, all current analyses focus on walking. As stated in section 2.1, cycling is a very popular mode of transportation in the Netherlands that is accessible to many people. This study aims the analysis on cycling, although it recognizes the importance of walking in the 15-minute city, aimed at inclusion and social interaction.

While there are many analyses of places as 15-minute cities, there are still dissimilarities in the services included in analyses, although these and the need for them might differ per case or location. Dimensions such as density and land mix, the catchment area of different services, capacity of different services, and the distances people are comfortable biking have not yet been fully quantified and might differ between countries or cultures. This flexibility of the concept is also acknowledged in (Chen & Crooks, 2021), who use an agent-based model to map walking communities in Queens, New York City.

Furthermore, needs for different socio-demographic groups within the 15-minute city have not yet been investigated, and if these are different at all. Additional exploration is needed to determine if and how the concept fits in the Dutch lifestyle of being used to cycling and often biking further than 15 minutes without problem, or to what extent travel behaviour in the Netherlands already takes place within 15 minutes from home by bike. Therefore, in this thesis, recorded travel data of people in the Netherlands will be used to explore the 15-minute city concept in a Dutch setting, and to operationalise the concept.

Lastly, many accessibility studies including cycling already exist, but often also include public transport (Mavoa et al., 2012; Yigitcanlar et al., 2007), or only consider one type of service (Apparicio et al., 2008; Apparicio et al., 2007; Páez et al., 2012). The 15-minute city is a holistic concept and cannot be properly captured by only considering one type of urban service. To conclude, a city (Utrecht) in the Netherlands will be assessed with regard to the established requirements and dimension of the 15-minute city. As stated in the introduction, Utrecht is the first Dutch city with ambitions to become a 15-minute (or rather a 10-minute) city. Their ambitions are further discussed in Appendix B. Additionally, through spatial analysis and regression, factors relating to the 15-minute city and its population will be investigated to find if spatial inequalities are present.

# 3. Study area and data

## *3.1 Study area*

The case study in this research focuses on the city of Utrecht and some surrounding towns. The study area includes the municipal area of Utrecht, and the towns Nieuwegein, Maarssen, Houten, Zeist, De Bilt, Bilthoven, and Bunnik. These towns were chosen because they are represented in the spatial strategy as new or existing centres for the polycentric structure (Gemeente Utrecht, 2021)(see also extended description of study area in appendix B). The study area consists of all neighbourhoods that have 1000 addresses/km$^2$ or higher within these towns, including the areas between these selected neighbourhoods, so as to not have gaps in the study area. The exact study area is shown in Figure 1.

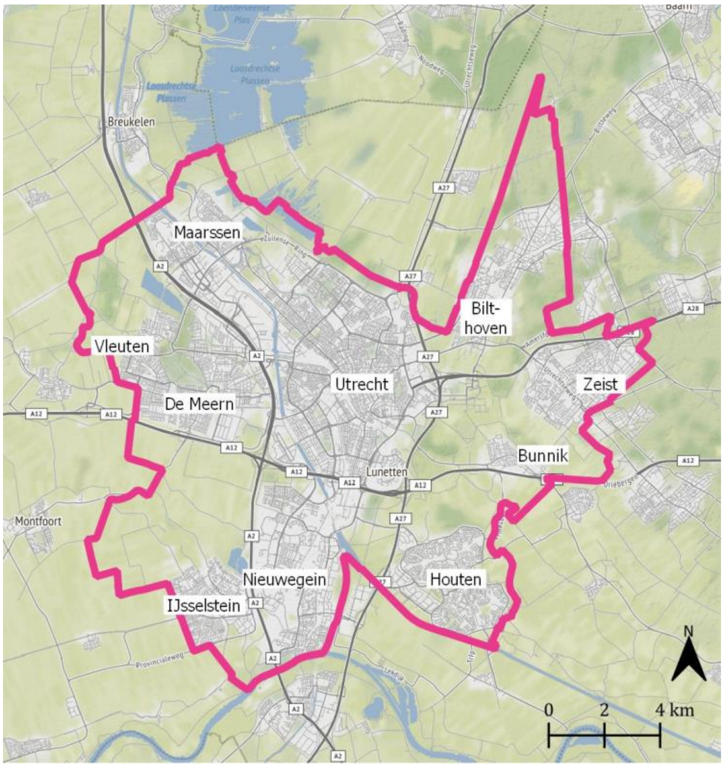


***Figure 1:*** *Study area*

The city of Utrecht is well-known as one where many people cycle due to the cycle-friendly infrastructure. 48.5% of all trips within the city of Utrecht are by bike. When trips to and from Utrecht are also included, 27.6% of all trips are by bike. The percentage of trips by bike that take place within the city is exceptionally high in Utrecht, compared to Amsterdam (42.6%).

## *3.2 Data*

The following types of data are used in this study; recorded travel data from the Dutch mobility panel (Dutch: Nederlands Verplaatsings Panel, NVP) that is used to develop the metric, and geographical data which is used for determining accessibility scores and finally the actual 15- and 10-minute city scores in the case study. Table 2 presents all data sources that are used in this study.

***Table 2:*** *Data sources*

| **Data** | **Description** | **Source** | **Year / time period** |
|---|---|---|---|
| NVP subset | Recorded trips from individual panel members | Dat.mobility | Dec 2019 – Feb 2020<br>June – July 2020 |
| CBS 500-by-500 m grid | Contains information on distance to services, socio-demographic information | CBS | 2018 (v3) |
| Bicycle network | Created from roads in OSM | OpenStreetMap (OSM) | January 2022 |
| POIs | Building file (polygons) and point file from OSM containing many different POIs | OSM | January 2022 |
| Parks and recreation areas | Land use file (polygons) from OSM containing many different kinds of land-use | OSM | January 2022 |
| Employment data | Point data, number of employment places per building | BAG, Dat.mobility | 2021 |

### *3.2.1 Recorded travel data*

Recorded travel data from the Netherlands mobility panel (NVP) was selected from all records based on a number of criteria. First, only trips made by people living in urbanisation level 1, 2, or 3 (>1000 people/km$^2$) were selected. Of these trips, trips with specific destination types essential to the 15-minute city were selected. Since the dataset consists of many different destinations, some were grouped to create the following nine destination types: *jobs* (everything ending in _office), *education, commercial* (everything containing _shop, commercial), *food* (grocery stores and other food stores), *bars and restaurants, sports, entertainment* (theatres), *recreation* (parks and playgrounds), *and healthcare* (doctor, health centre). Furthermore, only trips that took place between December 2019 and February 2020 (before Covid-19) were selected, as well as between June and July 2021 (during the pandemic, but when travel patterns were somewhat back to normal). All travel modes were included.

The selected NVP data consists of a dataset with trip records and one with user records. There are 233,273 trips in the trip dataset, and 21,556 records in the user dataset. After removal of duplicate records and records with urban density low or minimal (<1000 addresses/km$^2$), the user dataset consists of 8,214 unique users. Matching trip data with user data led to 225,958 trips with both trip and user information, excluding invalid trips with travel time 0 or travel mode unknown. Of these, 81,627 trips were made by bike.

### *3.2.2 Spatial data*

The spatial data includes the services in the study area and a 3 km buffer, origin points with data on residents, and the cycling network.

#### 3.2.2.1 <u>Origins and services</u>

For the GIS data, the CBS 500-by-500 m grid was chosen since it consists of equal sized squares, unlike the PC4 or PC6 polygons. A 100-by-100 m grid is also available, but the number of cells in the study area would be 25 times larger, around 55,000. Furthermore, 500-by-500 m cells are considered adequate for a study focusing on cycling, since cycling 250 m (from the centre to the edge) only takes roughly 1 minute at a speed of 15 km/h. The case study analysis output will thus be produced for this spatial unit. The 500-by-500 m data set contains information on inhabitants such as age groups, household characteristics, gender, and income. Using the building types of house or apartments in the OSM point data, the population weighted centroids of the cells in the 500-by-500 m grid is determined.

Destination data is filtered from OSM data as well. Table 3 presents the number of data points and description of each destination type. Polygon data containing all building is used to filter the buildings per destination type and create points at the polygon centres. Parks are selected from the land-use data in OSM, including the types *park*, *recreation ground, forest, and nature reserve*. Parks are intentionally left as polygons, with points created along the edges connecting to the road network as entrances for areas larger than 0.2 $km^2$.

The data sets for commercial and bars and restaurants contain 4,772 and 1,309 points respectively, much more than the other data sets (except jobs). For this reason, these points are aggregated to the 500-by-500 m grid with a point containing the number of shops or bars and restaurants at the weighted centroid (weighted by locations of the services).

Job data is available at the building level, in a BAG data file enriched by Dat.mobility. The data set contains the number of jobs per building. Using this dataset, all buildings with more than 0 jobs are aggregated in the same way as the commercial destination type, to the 500-by-500 m grid cells. A point containing the total number of jobs in the cell is located at the weighted centroid of each cell.

All destination data was selected within the study area and the 3 km buffer zone around the study area, because people living right at the edge of the study area can also travel to destinations just outside of the study area within 15 minutes.

***Table 3:*** *Destination data and description*

| Destination type | Nr of points | Aggregated | Description of destination type |
|---|---|---|---|
| Jobs | 30,334 | 1,326 | Exact number of jobs in each cell (2020) |
| Commercial | 4,772 | 667 | Number of shops in a cell excluding grocery stores, fresh produce, delis, and bakeries |
| Bars and restaurants | 1,309 | 297 | Number of bars, restaurants, cafés, coffee shops in a cell |
| Education | 573 | - | School, high school, or higher education |
| Food | 413 | - | Grocery stores, delis, bakeries, fresh produce |
| Recreation | 367 | - | Playgrounds, picnic sites, attraction |
| Parks | 213 | - | Green spaces |
| Entertainment | 193 | - | Museums, theatres, cinemas, community centres, libraries, nightclubs |
| Healthcare | 191 | - | General practitioners |
| Sports | 162 | - | Sports centres, gyms, pools, sports fields |

#### 3.2.2.2 Bike network

The bicycle network has been created from OSM road data. Use of the publicly available OSM data makes the method more easily reproducible. All roads with type cycleway, tertiary, living street, residential, unclassified, tracks, and secondary (only with 'both ways') were included in the bicycle network. Types footpath and pedestrian were not included. Even though it is possible to ride a bike on these, they are not meant for this purpose. Highways, primary roads, and secondary roads with only one direction were not included. The network was created in ArcMap, with nodes at every intersection between lines, and the possibility to ride both ways on all links. Travel time per link was calculated using an average speed of 15 km/h. Intersections were created where many nodes were located close together by clustering them and creating a polygon circle around each cluster. This was first done with traffic signal (point) data from OSM. Secondly, other junctions (without traffic signal) were also clustered. These intersections all got a polygon circle with radius of 25 m. For clustering, the DBSCAN algorithm in QGIS was used, with a maximum distance of 20 meters between points and a minimum of three points per cluster. The intersections with traffic lights got assigned a scaled cost (time) of 2.2 and the intersections without traffic light a scaled cost (time) of 2.6, since they are much smaller than the ones with traffic signals.

## 4. Methodology

In this thesis a composite indicator is developed that combines accessibility scores with importance of different destinations (through weights as derived from NVP data). The following subsections present the conceptual model of the metric, the accessibility measure used, and the methods used for sensitivity analysis and spatial regression of the results. Methodology used for response weighing of the NVP data, linear regression of the cycling speed in NVP data and constructing the distance decay functions used in accessibility measures can be found in Appendix C.

### 4.1 15-minute city metric

#### 4.1.1 Conceptual model

Several dimensions influence to what extent a place can be considered a 15-minute city. First of all, the built environment; a (safe and well connected) cycling and pedestrian network, the locations of services and their diversity. On the other hand, people's behaviour influences if a place is a 15-minute city. What destinations do they find important and visit every day? How far are they willing to bike (or walk) to these places and what is their speed? A grocery store 15 minutes away may push some people to use the car, while biking 15 minutes to work is considered more acceptable. People of different ages or social environments also have distinct needs and mobility patterns (see appendix D.1, D.2, D.3 and D.4) and thus a place might not be a 15-minute city for everyone but only for some.

The developed 15-minute city metric consists of built environment factors and behavioural factors. While the quality of the cycling network is important it is out of scope for this study. The cycling network used in analysis consists of every space where a bike can be driven but does not include penalties for unsafe situations. Other than the waiting time at intersections, there are no penalties for barriers such as crossing large roads. Thus, the built environment factor is represented in the cycling network and the locations of destinations. The behavioural factor is captured in the average speed of cyclists as determined through analysis of recorded trip data, distance decay functions, and revealed importance of services by visits to different destination types (see descriptive statistics in appendix D.1). The conceptual model of the metric is presented in Figure 2.

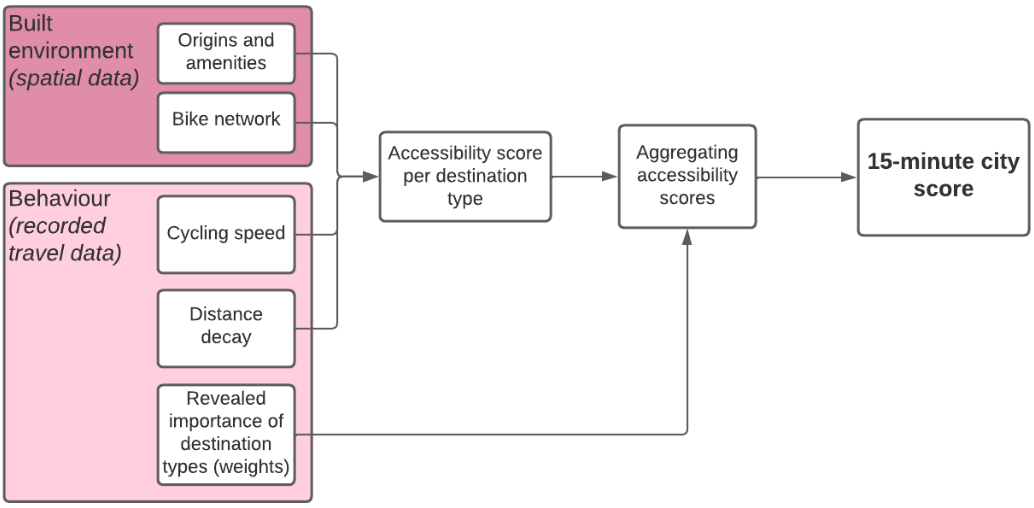


***Figure 2:*** *Conceptual model of the metric*

#### 4.1.2 Accessibility score per destination type

For the accessibility measures it is important that availability of services in the 15-minute city are taken into account. For example, there might be a school close to one's place of residence, but if this is the only school in a densely populated neighbourhood, not every child in the neighbourhood can attend this school. The neighbourhood is not a 15-minute city anymore. According to (Penchansky & Thomas, 1981), access (to healthcare) has 5 dimensions; accessibility, availability, accommodation, affordability, and acceptability. 2-step Floating Catchment Area (2SFCA) takes into account two of these dimensions (accessibility and availability). Using 2SFCA as the accessibility measure, the ratio of population to a service (such as education) is incorporated. Thus, supply and demand are both considered, instead of only the supply. To fully capture the difference between small and large schools, or doctor's practices for example, the capacity would have to be taken into account as well. However, this requires data that was not available in this study.

Usually, in more densely populated areas, more services of a specific type are located, but there are also more people using these. A higher density neighbourhood might need and have more of a specific service to provide for their residents. Using 2SFCA this fact will be accounted for, and the accessibility measure will thus be fairer since it is taken into account how many people will have the chance to go to an opportunity. 2SFCA is more suitable for some destination types such as education, healthcare, and jobs. Many studies have used some form of 2SFCA for measuring spatial accessibility to healthcare (W. Luo & Wang, 2003). Ye et al. (2018) use an enhanced version of 2SFCA to measure accessibility to education in China. They also take into account school size (nr. of students) and quality of the school. (Xiao et al., 2021) use 2SFCA to measure job accessibility in China, for multiple modes and take into account the number of jobs at each location. 2SFCA has also been used to measure accessibility to sports facilities in Wales (Langford et al., 2018), and to green spaces (Qiu et al., 2019; F. Wang & Wang, 2018) in both of which the area ($m^2$) of the park or recreation space is incorporated in the measure. Furthermore, (Qiu et al., 2019) consider different walking speeds for different age groups, and thus all age groups have different catchment areas.

(J. Luo, 2017) measured accessibility to food stores in Springfield, Missouri using 2SFCA and taking into account square footage of the stores. In addition to this, the probability of someone visiting a specific store is incorporated, based on attractiveness or capacity of the store and the competing stores, and on the travel cost to the store.

No previous studies were found that had used 2SFCA (or a modification) to measure accessibility to shops or restaurants, which are two of the destination types included in this thesis. It can be argued that these types are not appropriate to be measured by 2SFCA because they do not really have a capacity like some of the other destination types do (students in a school, jobs at a workplace, area of sport facilities). However, restaurants do have a capacity that is also tied to a temporal dimension, although this is relatively hard to account for. 2SFCA is also able to capture the fact that (mostly) there are more restaurants and shops in denser populated areas, and less in more sparsely populated areas. This means that these lower density areas need less shops and restaurants to still be considered just as much as a 15-minute city as the densely populated city centres. 2SFCA allows for scaling to the population size of a place.

Thus, the metric will consist of 2SFCA gravity-based accessibility measures that take into account the age of residents in the area. The different age groups are used for the calculation of the demand for the service in the area, applying their respective distance decay functions detailed in Appendix D.4. The same cycling speed is used for all age groups.

Accessibility for grid cell i for destination type p then becomes:

$$A_{i,p} = \sum_j^n \frac{S_j * f(c_{ij})}{D_j} \tag{1}$$

With the demand D for every destination j being:

$$D_j = \sum_k^m \sum_q^r P_{k,q} * f\left(c_{kj}\right)_q \tag{2}$$

Where q = {1, ..., r} are the 5 age groups, j = {1, ..., n} are the destinations (of type p), k = {1 ,..., m} are the origin cells for the demand, and $f(c_{ij})_q$ is the distance decay function for age group q.

The supply of the destination type is calculated using the general distance decay function (for that destination). The demand $D_j$ is calculated per age group and multiplied with the size of that group $P_{k,q}$ in cell k. Demand is taken from all cells k which can reach service j within the threshold time.

Supply is calculated for the study area and 3 km buffer zone, for destination just outside of the study area. Demand is calculated for this area, including another buffer zone, since people living just outside the buffer zone can also travel to destinations in the 3 km buffer zone.

Thus, the accessibility measure can be interpreted as the number of services of a specific destination type that are available for grid cell i per person, within the specified threshold time.

#### 4.1.2.1 Considerations per destination type

Minor differences are made in the calculation for some destination types. The food, healthcare, entertainment, restaurants, commercial, recreation and sports types are calculated as normal. However, for education, the demand is calculated for people aged 24 or lower only. Furthermore, it is worth noting that the dataset for education contains schools, elementary schools, and higher education, and these locations do not contain information on number of enrolments or capacity in any other form. For jobs, the demand is calculated only for people aged between 15 and 65.

The aggregated point data contains number of employment positions per location. Finally, the parks have multiple entry points and thus multiple routes leading from one origin cell to the same park. For each combination, only the shortest route is taken into account. Thus, each park is only counted once, and size or area is not taken into account.

#### *4.1.3 Aggregating accessibility scores*

To aggregate the accessibility scores into one metric, they should first be standardized so that they are all on the same scale. The accessibility scores are standardized based on their range, i.e., the highest score minus the lowest score, according to the following formula:

$$X_{i,p} = \frac{A_{i,p} - min\ (A_p)}{max(A_p) - min\ (A_p)} \tag{3}$$

Weighing the accessibility scores is done because not every destination type is as important.

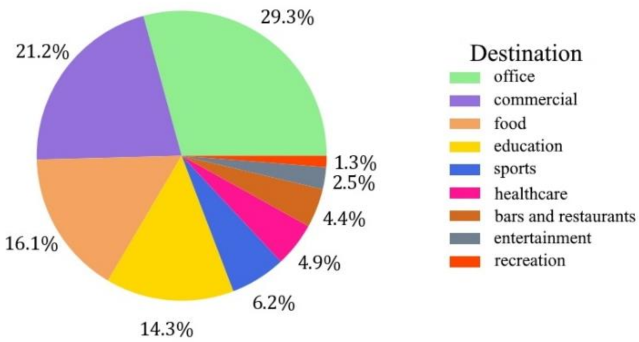


*Figure 3: Percentage of trips (all modes) per destination type*

Weights are derived from the trip distribution as shown in Figure 3 and Appendix D.1. As discussed in section 3.2.1 and appendix D.1, for the NVP dataset, it should be taken into account that some destinations were visited less because of Covid-19 or difficulty detecting destination.

The final metric is then defined by the equation:

$$CS_{x,i} = \sum_{p=1}^{P} w_p * X_{i,p} \tag{4}$$

Where $CS_{x,i}$ denotes the x-minute city score with travel time threshold x in cell i, $w_p$ the weight of destination type p, and $A_{i,p}$ the accessibility score of destination type p in cell i. The metric is calculated for three different travel time thresholds; 10, 15 and infinite minutes (in reality 130 minutes because no destinations were further than 130 minutes cycling within the study area). From here on denoted as $CS_{10}$, $CS_{15}$, and $CS_{\infty}$.

### *4.2 Sensitivity analysis of 15-minute city metric*

Composite indicators, and the 15-minute city metric, consist of different sub indicators weighted and aggregated into one value. In the case of the 15-minute city metric, the accessibility scores for the destination types are the sub indicators. However, each accessibility score, as well as its weight, possesses some uncertainty. Uncertainty in the accessibility scores themselves can stem from uncertainty in the travel times on the network links in the study area. This type of uncertainty is out of scope for this study. However, uncertainty in the weight of each destination type is assessed, and stems from the method of determining the weights (recorded trips). Other methods might yield different results, as for example Weng et al. (2019) derive very different weights per destination type through a survey.

In order to evaluate for robustness of the 15-minute city metric and assess how much of the uncertainty in the weights contributes to the output value variance, uncertainty and sensitivity analysis are applied. In uncertainty analysis (UA), the way in which uncertainty of the weights affects the value of the indicator under study is analysed. In Sensitivity analysis (SA), it is determined how much the uncertainty of each weight is represented in the variance of the metric output (Saisana et al., 2005). To do this, distributions of the weights are specified between 0 and 0.294, the maximum value of the job weight. Including weights of 0 leads to excluding one or more destination types in some samples. Thus, both selection of sub indicators and weighing scheme are addressed in the uncertainty analysis (OECD, 2008). Using the SALib package for python (Herman & Usher, 2017), 512 different values for each weight are specified and combined to a unit-sum of 1. A sample of 11,264 combinations of the weights is generated.

For UA, the variance in the generated outputs with the new combinations of weights is visualised. For SA, the amount of uncertainty stemming from each weight is measured using the sensitivity index, using the SALib package. The sensitivity index ($S_i$) of variable i can be interpreted as the percentage contribution to the model output variance stemming from the uncertainty in that weight. Additionally, the total sensitivity index ($S_{Ti}$) is recorded, which states the contribution to the output uncertainty of the input i and all its interactions with the other inputs. SALib calculates the sensitivity index and the total sensitivity index.

Results from the sensitivity analysis are presented in appendix D.5.

### *4.3 Spatial analysis*

#### *4.3.1 Spatial statistics*

Spatial statistics provide ways to analyse relationships in a spatial context. Local Moran's I used to calculate and visualise clusters and outliers (Moran, 1950). One variable (the $CS_{10}$ or $CS_{15}$) is analysed to discover areas where high values are grouped together (spatial autocorrelation). Spatial outliers can also be discovered using Local Moran's I, which can either be high values surrounded by low values or low values surrounded by high values. An adjusted version of Local Moran's I called bivariate Moran's I is used to analyse correlation between two variables and their clustering (spatial correlation) (Lee, 2001) and was used by Weng et al. (2019) to analyse the correlation of neighbourhood walkability for a specific population group and the population of that group in the neighbourhood.

Global and local Moran's I are calculated for both the $CS_{10}$ and $CS_{15}$. Additionally, bivariate local Moran's I is applied to the elderly population and the $CS_{10}$ calculated for this specific group, as well as the $CS_{10}$ with percentage people with immigration background, percentage people receiving welfare, percentage social housing, percentage children, and percentage people living below social minimum.

#### *4.3.2 Spatial modelling/regression*

Additionally, three different models are applied to gain insight into the relationship between the CS and some neighbourhood and population characteristics. First, Ordinary Least Squares (OLS) to the non-spatial data. Spatial lag model and a combined spatial lag and error model are subsequently applied to account for autocorrelation in the residuals of the OLS model. When geographical relationships are at play, such as the accessibility to different services, the explanatory variables cannot explain the dependent variable completely, and a (large) part may be explained by spatial dependence. Tobler's first law of geography says that "everything is related to everything else, but near things are more related than distant things." (Tobler, 1970). If the residuals of a linear regression show spatial dependence, investigated by global and local Moran's I, spatial regression models can be applied to account for this spatial dependence (L. Anselin, 1988). Lagrange Multiplier tests are conducted to investigate which type of spatial dependence is present and should be modelled; if the LM test for spatial lag is significant, the spatial lag model should be applied. If the LM test for spatial error is significant, this model should be applied (Chi & Zhu, 2020). Values and statistical significance for LM tests are included in the OLS model results in appendix E.7.

The dependent variable used in all models is the $CS_{10}$ excluding job opportunities. The $CS_{10}$ is chosen as dependent variable because Utrecht has ambition to become a 10-minute city. The analysis unit is still the grid cells of 500-by-500 m, which include a number of variables on socio-demographic factors as well as physical neighbourhood characteristics (CBS, 2018). Appendix E.8 presents results for the spatial regression using the $CS_{10}$ including jobs.

The independent variables included in the model (model A) are based on factors indicating risk at transport poverty according to Kampert et al. (2018) and Jorritsma et al. (2018). Transport poverty entails the inability to access locations or opportunities and a disadvantage at partaking in society as a result (Kampert et al., 2018). The identified factors were low income or unemployment, old age (>65) as well as young age (<15), having an immigration background, not having a driver's license, not having a car, having a mental or physical disability, and distance to public transit stops. Data on driver's license and disabilities is not included in the data, so these factors were left out of analysis. In order to determine independent variables to be included, correlation between them and the dependent variable was investigated, as well as correlation between the independent variables to avoid multicollinearity in the model (see Appendix E.5 and E.6 for correlation matrix and scatter plots of the independent variables with the dependent variable).

A second model, model B, consists of the same variables as model A while also controlling for some extra physical neighbourhood characteristics available in the data that had individual correlations with the $CS_{10}$. The variables that are included are listed below in Table 4. Variables such as distance to highway access, car possession, and housing price were left out due to little or no correlation with the dependent variable.

***Table 4:*** *variables used in the regression models*

| Variable | Description | Unit | Model |
|---|---|---|---|
| % soc. minimum | Percentage of households living under or just around social minimum, households of which at least one person makes money all year round, but below the social minimum as defined by the government | % | A, B |
| % welfare | Percentage of people receiving benefits from the government because they are unemployed or unable to work | % | A, B |
| % > 65 years | Percentage of residents over 65 years of age | % | A, B |
| % < 15 years | Percentage of residents under 15 years of age | % | A, B |
| % immigrants | Percentage of residents that were born outside of the Netherlands or whose parents were born outside of the Netherlands | % | A, B |
| D train station | Distance to the nearest train station | km | A, B |
| % < 1945 | Percentage of residencies built before 1945 | % | B |
| % > 1994 | Percentage of residencies built after 1994 | % | B |
| % apartments | Percentage of residencies that house more than one family (i.e., apartment buildings) | % | B |
| Income | Mean yearly income per person (before tax) | [€ x 1000] / year | B |
| Pop. density | Residents per km2 | [People x100]/km2 | B |

#### 4.3.2.1 Spatial lag model

A spatial lag model, similar to a standard linear regression, finds coefficients for the explanatory variables, but includes a spatial lag coefficient that autoregresses the response variable. Thus, the prediction at a location is influenced by the dependent variable values of its neighbours, as specified in a spatial weights matrix (L. Anselin, 1988; Chi & Zhu, 2020).

The regression equation of a spatial lag model is as follows:

$$Y = \beta_0 + X_1\beta_1 + X_2\beta_2 + \cdots + X_k\beta_k + \rho WY + \varepsilon \tag{5}$$

Where Y denotes the value of the response variable, β the coefficients of the explanatory variables X, and ε the error terms that are normally distributed. In addition to this, ρ denotes the spatial lag parameter and W the spatial weight matrix. WY denotes a spatially lagged variable and is a weighted average of the response variables in the neighbourhood.

#### 4.3.2.2 Combined spatially lagged and error models

In a spatial error model, the dependent variable at a location is influenced by the average residuals or errors of its neighbours, as specified in a spatial weights matrix. A model combining spatial lag dependence and spatial error dependence simultaneously is also known as a spatial autoregressive moving average model (SARMA)(Anselin & Bera, 1998). The model is specified as follows:

$$Y = \beta_0 + X_1\beta_1 + X_2\beta_2 + \cdots + X_k\beta_k + \rho WY + u,\ u = \lambda Wu + \varepsilon \tag{6}$$

Again, ρ denotes a spatial lag parameter, and λ a spatial error parameter. *WY* is again a spatially lagged variable, a weighted average of the response variables in the neighbourhood. *Wu* is a spatially lagged error term, a weighted average of the error terms in the neighbourhood.

#### 4.3.2.3 Spatial weights matrix

Both spatial lag models and combined lag and error models can be judged on their fit through assessing log likelihood values or AIC values. In order to pick the best fit of all models, 3 different spatial weights matrices were specified, since the type of spatial weights matrix can influence the model results (Chi & Zhu, 2020). A 4-nearest neighbour, Queen, and Rook spatial weights matrix are tested with the spatial models. Queen spatial weights includes every neighbour that a cell shares an edge or a vertex with, while Rook spatial weights matrix only includes those that share an edge. See also Figure 4. The type of spatial weights matrix is included in the model results.

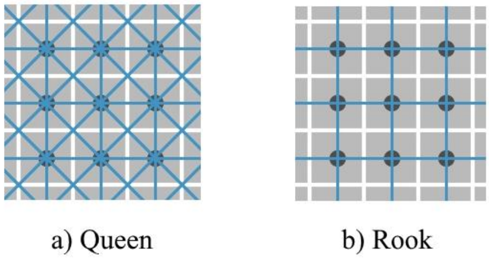


***Figure 4:*** *Spatial weights matrices*

### *4.4 Scenario analysis*

A scenario is created to evaluate traffic measures in the network, based on some existing plans and studies regarding new bridge or tunnel connections for cyclists in the study area. The scenario was assessed using the metric to see how these measures affect the 15-minute city. 9 bridge/tunnel connections are added in the network, based on the report for new cycling connections from Gemeente Utrecht (Gemeente Utrecht, 2019). The report specified thirty-five possible new connections, nine of which were prioritised to be implemented on relatively short term (by 2025). These nine are shown in **Figure 5** and were added in the network.

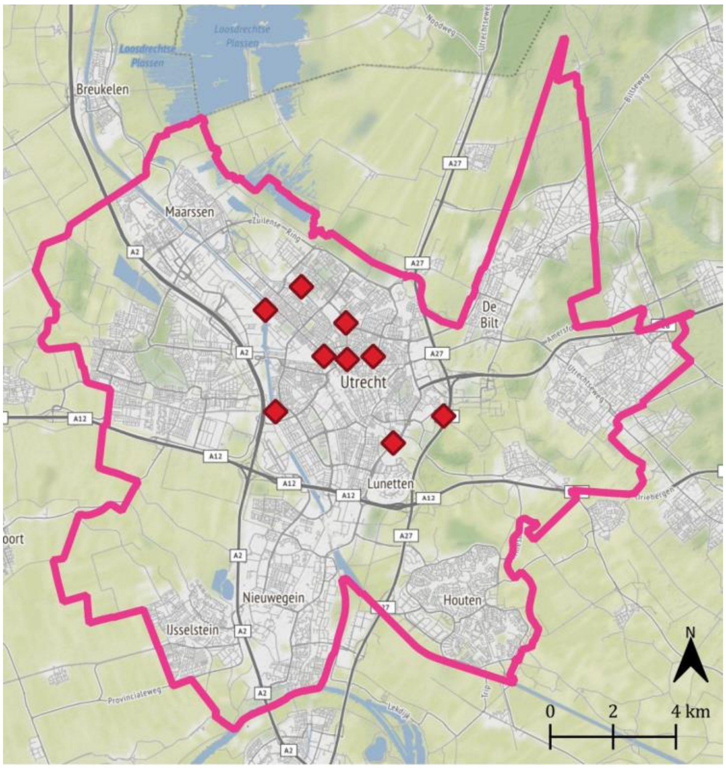


***Figure 5****: Newly planned cycle bridges and tunnels in the study area*

It should be noted that since these plans are from the municipality of Utrecht, the bridges and tunnels are only planned within the municipal boundaries (smaller than the study area). After adding the new connections in the network, the metric is calculated again. The origins and destinations remain the same as in the base scenario.

## 5. Results

In the following sections, the results of analyses are presented and described. Additional results are presented in Appendix D, and additional figures and tables in Appendix E. Results of the mobility analysis including descriptive statistics, ANOVA and linear regression on cycling speed, and distance decay functions can be found in Appendix D1, D.2, D.3, and D.4. Results of the sensitivity analysis are presented in Appendix D.5.

Because the fit of the regression model on cycling speed was very poor ($R^2 = 0.033$) (Appendix D.3), and the minor differences in cycling speed between groups found in ANOVA (Appendix D.2), it was decided to use a single average cycling speed of 15 km/h in further analyses. This is slightly higher than the average speed found in the data (13.8 km/h) but will be used in combination with network characteristics in the intersections, where wait times are added (see section 3.2.2). This is assumed to be a more realistic approximation of cycling speed.

### *5.1 Accessibility analysis*

The accessibility per destination type is calculated for two threshold travel times: 15 and 10 minutes, considering both the basic 15-minute city concept and the 10-minute city goal of Utrecht. Results of the analysis with threshold travel time of 10 minutes are presented in Appendix E.2, while results of the 15-minute travel time threshold are presented in Figure 6. Scores are standardized according to the lowest and highest values found in the 10-minute analysis, since these contained both the highest and lowest values. Thus, results of the 15-minute analysis can be compared to those of the 10-minute analysis. The standardized scores, as expected, generally show larger areas with relatively high scores for 15 minutes than for the 10-minute threshold, which are more concentrated in certain areas and are also generally higher in these (smaller) areas.

Results of the 15-minute threshold are relatively smooth, while those of the 10-minute analysis show some outliers because results were standardized according to this distribution. Also, some areas in the 10-minute analysis have a score of 0, as well as one grid cell in Bilthoven in the 15-minute analysis in the entertainment category. 0 scores can be found in the 10-minute analysis in the northeast of Bilthoven for entertainment, and for the south of Houten for healthcare and sports categories. Some areas in IJsselstein and Maarssen score 0 for sports as well. 0.78% of the population do not have access to entertainment, 1.56% to healthcare, and 5.07% to sports destinations within 10 minutes cycling. These three categories (entertainment, healthcare, and sports) are not accessible for everyone within 10 minutes cycling, where most prominently sport destinations are inaccessible for relatively more people. With the 15-minute threshold, there is only one grid cell with a score of 0 for the entertainment category, which is equivalent to 0.08% of the population in the study area.

Commercial, bars and restaurants, and entertainment categories score relatively high in the city centre of Utrecht, while scores for healthcare, parks, recreation, and jobs are not so concentrated in the city centre. In the 10-minute analysis, differences between city centre and surrounding areas are very prominent in the commercial and bars and restaurants category. Education scores highest around the university of Utrecht, located just east of the city centre (between Utrecht and Bunnik). Interestingly, scores for sports are highest just around the city centre of Utrecht, suggesting a high supply for the population still in Utrecht but on the edges of the city. This makes sense since sport parks and fields are mostly located on these edges. Furthermore, the scores for healthcare are notably high in Bilthoven and Zeist. These towns have a slightly lower density but a relatively high number of general practitioners. It is possible that there are more small practices in these towns, while there may be more large practices in the city of Utrecht. However, the capacity of services was not considered in this analysis and the data does not show this. Recreation scores highest in Houten in the southeast, which is a typical growth centre town from the 1988 and 1991 spatial planning policies in the Netherlands (Min. VROM, 1988; Min. VROM, 1991) and has many playgrounds for children. However, on almost all other categories except entertainment, Houten scores relatively low.


***Figure 6:*** *Standardized accessibility scores per destination type, 15-minute maximum travel time*

Nieuwegein (in the south) scores slightly higher in the job category, as well as part of Maarssen (in the northwest). These cells are close to industrial areas where a lot of job positions are located. Another area that scores a bit higher for jobs is located around the university and hospital. Nonetheless, the scores in the job category in the 15-minute analysis are all relatively low.

Finally, scores for food category in the 15-minute analysis are relatively homogenous for the study area and neither extremely high nor extremely low. Some higher scoring areas can be found in the city centre of Utrecht, as well as the town centres of the suburbs. Thus, access to grocery and other food stores is equally distributed throughout the study area.

### *5.2 x-minute city scores*

Aggregating the accessibility scores according to the weighing scheme and weights provided in section 4.1.3, the results are calculated for the 10-minute threshold, 15-minute threshold, and no travel time boundary. The results are presented in Figure 7. Since all scores are standardized according to the 10-minute scores distribution (both highest and lowest outliers), the results are all on the same scale and can be compared to each other. Appendix E.3 presents results in- and excluding the job category from the destination types, but results are quite similar. Overall, $CS_x$ excluding the job category are slightly higher everywhere, because job scores are relatively low in almost the entire study area (see Appendix E.2 and Figure 6) and have a high weight.

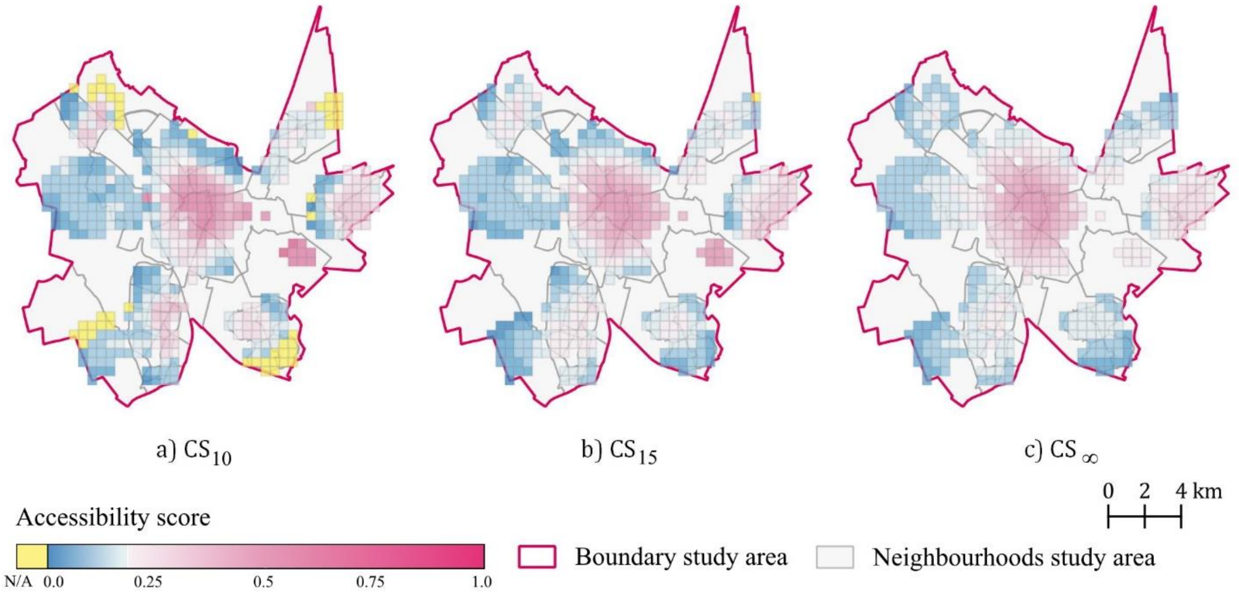


***Figure 7:*** *$CS_{10}$ , $CS_{15}$ , and $CS_{\infty}$*

The most prominent difference between the $CS_{10}$ and the $CS_{15}$ is the presence of grid cells with no score in the $CS_{10}$. These grid cells do not have accessibility to one or more of the destination types. As can be seen in Appendix E.2, these categories are sports, healthcare, and entertainment. On the other hand, in the $CS_{15}$, there is only one grid cell in Bilthoven at the edge of the study area that has no score. Naturally, without a travel time threshold, all grid cells can reach any destination type and thus have a score. By this definition, a mere 5.76% of the population in the study area do not live in a 10-minute city, for the 15-minute city this number drops to a marginal 0.03%. Thus, overall the study area performs very good as a 10- or 15-minute cycling city.

The overall $CS_{10}$ show high values in the city centre of Utrecht and in Bunnik. Also, in the surrounding towns, the centres score higher than the edges. The $CS_{15}$ results are more homogenous, but still the highest scores can be found in the city centre of Utrecht and in Bunnik. Lower values are found in IJsselstein and Houten.

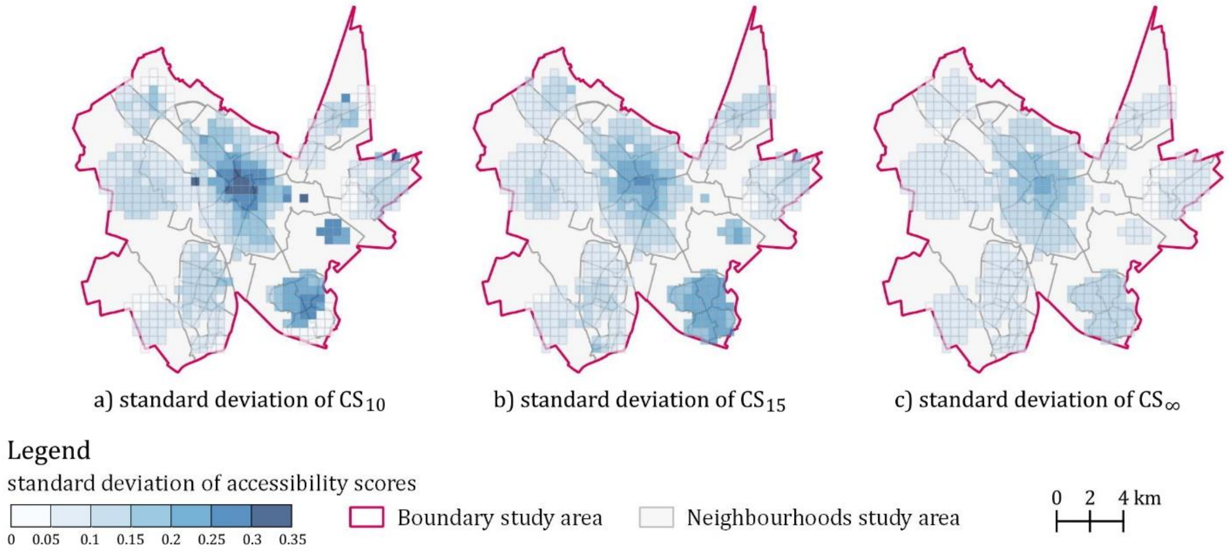


***Figure 8:** standard deviation of underlying accessibility scores of $CS_x$*

Figure 8 presents the standard deviations of the accessibility scores per destination type within each cell. Evidently, while the $CS_{15}$ and the $CS_{10}$ are high in the city centre and in Bunnik, the standard deviation is also relatively high, meaning that some categories might score very high while others score substantially lower. Houten, while scoring low in both the $CS_{10}$ and $CS_{15}$, has a high standard deviation as well, indicating some problematic supply of certain destination types but also some destination types with good practice.

Figure 9 shows the absolute difference between the scores with different thresholds. The difference between the $CS_{15}$ and the $CS_{\infty}$ are relatively small, as can be seen in Figure 9c. Only in Bunnik is the difference in score more considerable, with $CS_{15}$ being substantially higher than $CS_{\infty}$.

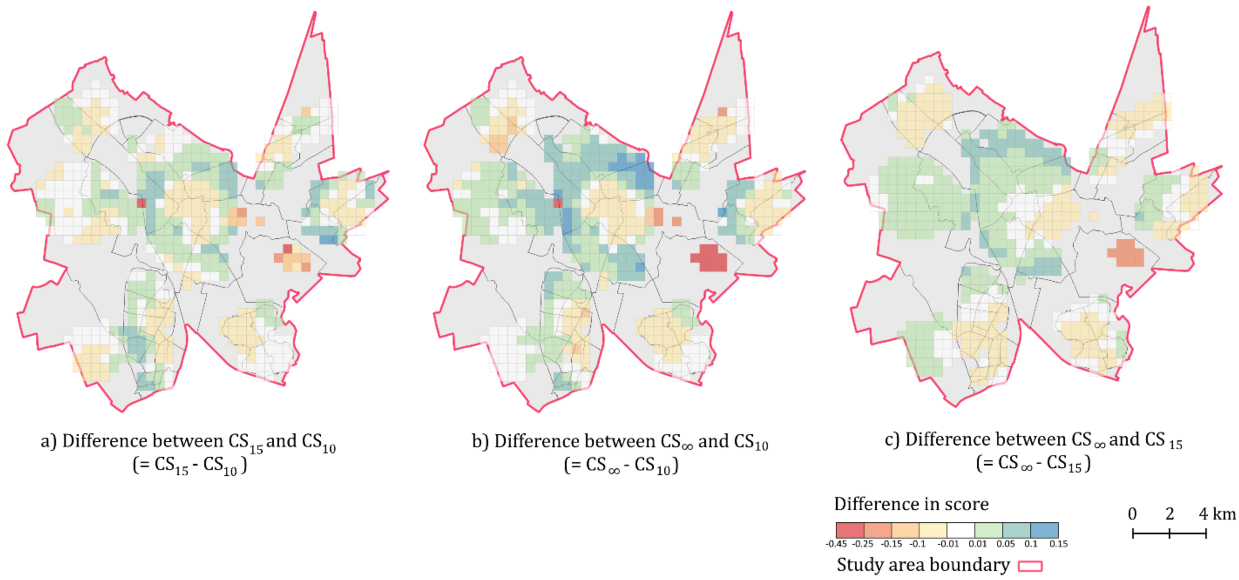


***Figure 9:** Differences in $CS_{10}$, $CS_{15}$, and $CS_{\infty}$*

However, differences between $CS_{15}$ and $CS_{10}$, and between $CS_{10}$ and $CS_{\infty}$, shown in Figure 9a and b, are more substantial. Scores in the area around the city centre of Utrecht are generally lower when travel time is lower. Thus, people living in the areas around the city centre are especially disadvantaged by a lower travel time, meaning they have to travel further to find the same number of opportunities as someone living in the city centre. On the other hand, $CS_{10}$ is substantially higher than $CS_{15}$ and $CS_{\infty}$ in the city centre. People living here benefit from the lower travel time, but only if people in the other neighbourhoods also stay in their own neighbourhood – can find their daily needs within

10 minutes cycling – because otherwise demand is too high. Thus, people living in the city centre might benefit from the other areas scoring higher as a 10 or 15-minute city. Though it should be noted that the higher demand from the $CS_\infty$ may be showing a more realistic image for the commercial and entertainment categories for example, because the city centre of Utrecht attracts people from much further than just the 10 or 15-minute boundary.

### 5.3 *Spatial analysis*

Table 5 shows the global Moran's I statistics of the $CS_{10}$ and $CS_{15}$ in the study area. These were calculated using the spatial weights matrix of the 8 nearest neighbours, since a square surrounded by other squares has 8 direct neighbours. The z- and p-value show that the overall results are highly clustered.

***Table 5:*** *Global Moran's I statistics of $CS_{10}$ and $CS_{15}$*

| | $CS_{10}$ | $CS_{15}$ | $CS_{10}$ (no jobs) | $CS_{15}$ (no jobs) |
|---|---|---|---|---|
| I | 0.74459 | 0.77903 | 0.80644 | 0.80845 |
| z-value | 35.6557 | 37.3005 | 38.6096 | 38.7057 |
| p-value | 0.000 | 0.000 | 0.000 | 0.000 |

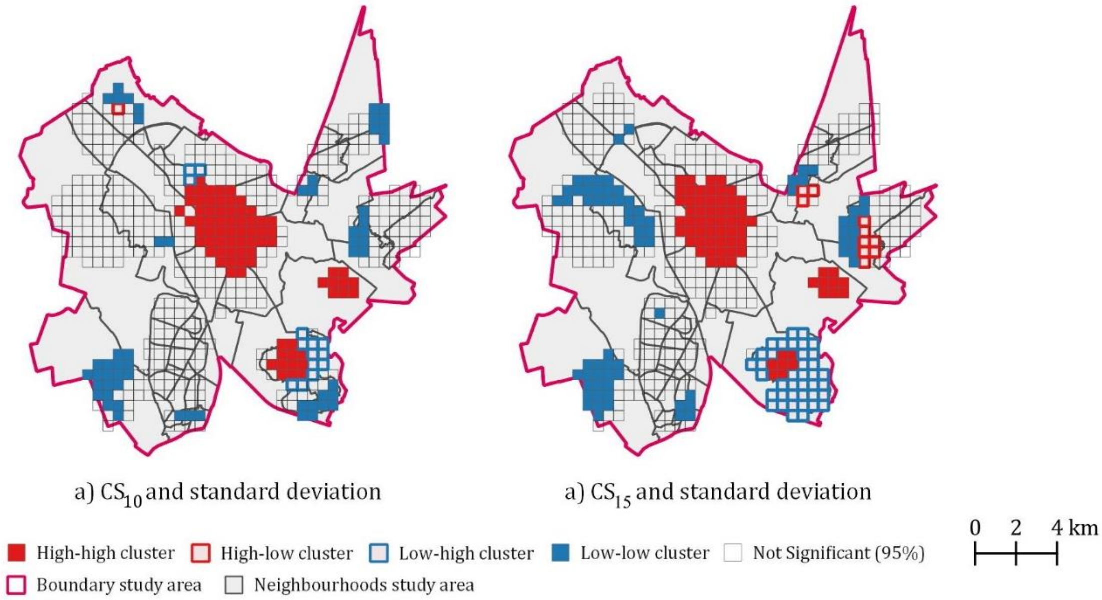


***Figure 10:*** *Bivariate local Moran's I of $CS_{10}$ and $CS_{15}$ and standard deviation*

Figure 10 shows the bivariate local Moran's I (spatial correlation) of the $CS_{10}$ and $CS_{15}$ and their standard deviations. This provides insights into the accessibility scores underlying the $CS_{10}$ and $CS_{15}$ without having to look at the individual scores. While the city centre of Utrecht scores high in both cases, the standard deviation is also high, thus some destination types may have a low score and be underrepresented. The same is true for Bunnik and Houten. Contrarily, the rest of Houten scores low and has a high standard deviation, so some destination types may still have a high score. Finally, some interesting clusters are the high-low ones, with a high $CS_{10}$ (in Maarssen) or $CS_{15}$ (Bilthoven and Zeist), and a low standard deviation. These areas have more homogenous accessibility scores for the individual destination types and can thus be considered better 15-minute cities.

Figure 11 presents bivariate local Moran's I for the $CS_{10}$ and some socio-demographic and neighbourhood characteristics. It shows a low-high cluster for the $CS_{10}$ with percentage people with immigration background, percentage people receiving welfare, and percentage social housing in the neighbourhood Overvecht in Utrecht (centre-north). The $CS_{10}$ here is low, but these characteristics are high. The people that live here are largely economically disadvantaged and have a greater risk at transport poverty (Kampert et al., 2018) and according to the

$CS_{10}$, have less access to the services of the 10-minute city. It should be noted that people with immigration background generally cycle less than native Dutch people overall (Harms et al.,2014; Nello-Deakin & Harms, 2019).

On the other hand, Kanaleneiland (neighbourhood in southwest of Utrecht), shows high-high clusters in for the $CS_{10}$ and the percentage people with immigration background, percentage people receiving welfare, and percentage of social housing. This indicates Kanaleneiland as a better practice neighbourhood where people with lower income and immigration background also have access to the services of the 15-minute city.

While cycling rates have been increasing among people with immigration background in the past decade, according to (Nello-Deakin & Harms, 2019) people with immigration background cycle less than native Dutch people, regardless of environmental characteristics. Thus, it may not matter if they live in a 15-minute city in terms of cycling rates. Instead, other incentives or nudges might be needed to increase cycling rate in this group, such as education.

Figure 11e shows a strong relationship between percentage of children and the $CS_{10}$. Where $CS_{10}$ is low (in Vleuten-De Meern and the south of Houten), percentage of children is high, while the $CS_{10}$ is remarkably high in the city centre but relatively few children live here. Figure 11f shows the correlation between the $CS_{10}$ and percentage elderly. Similar to the children, the $CS_{10}$ is high in the city centre but relatively few elderlies live here. the $CS_{10}$ is relatively low in parts of Bilthoven, Maarssen and the south of Nieuwegein, while percentage of elderly is high in these neighbourhoods. Some notable high-high clusters are located in Zeist and Bunnik, where elderly live in a 10-minute city.

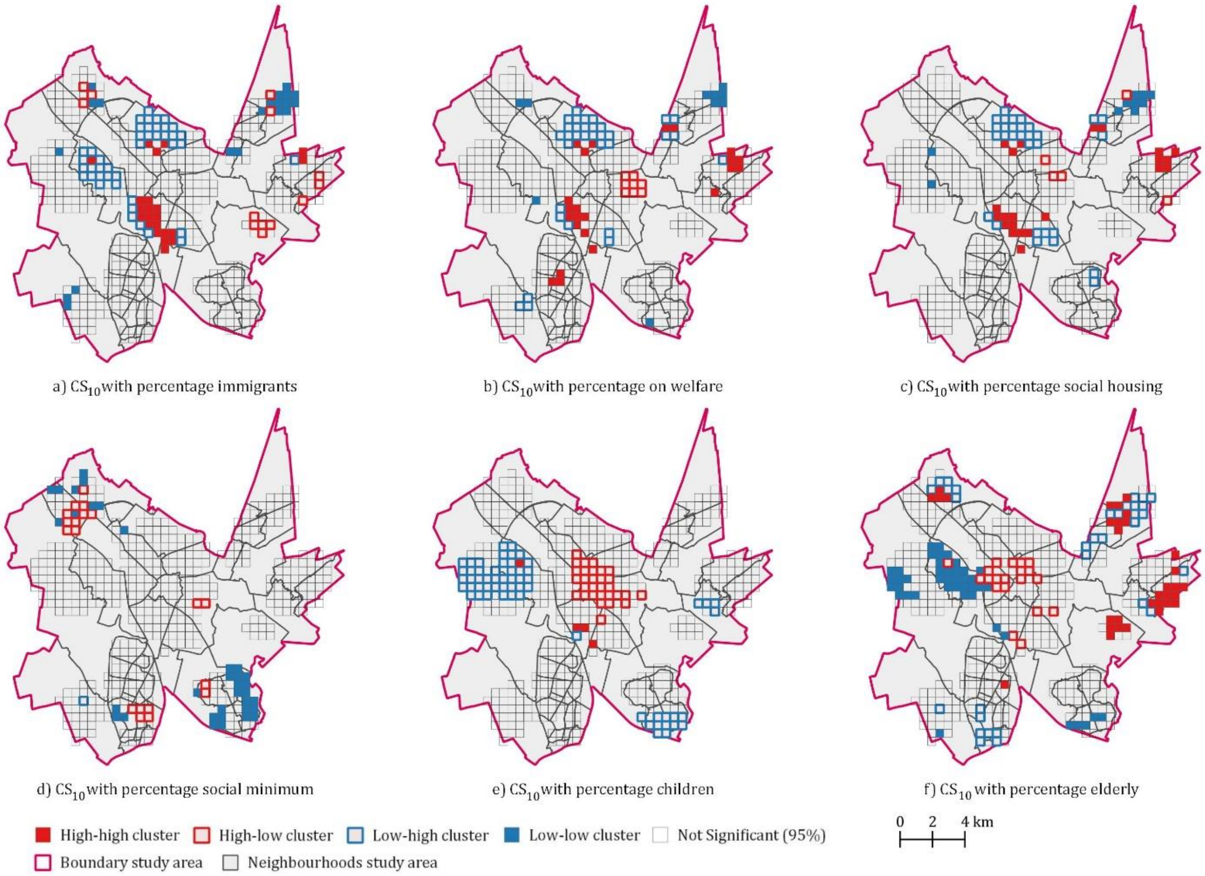


***Figure 11:** Bivariate local Moran's I of $CS_{10}$ and other characteristics*

### *5.3.1 Spatial regression*

In order to find potential relationships between residents' and neighbourhood characteristics and the $CS_{10}$, (spatial) regression is applied. First, an ordinary least squares (OLS) linear regression is run on the data. To achieve a more normal distribution of the dependent variable ($CS_{10}$), it was first changed to a log scale by taking the natural logarithm of the $CS_{10}$, see Figure 12.

Ordinary Least Squares linear regression was first performed. Results are presented in Appendix E.7. spatial diagnostics were included to determine the appropriate spatial model (error model, lag model, or combination). Model

A includes the variables indicated in the literature about transport poverty, and model B includes those and physical neighbourhood characteristics. In both OLS models, the Moran's I statistics of the residuals (based on the 4-nearest neighbour spatial weights matrix) show statistically significant spatial dependence, thus the residuals are clustered. Furthermore, for both models the Lagrange multiplier (LM) for spatial lag and error dependence are strongly significant. The robust LM tests for model A show only significant spatial dependence for lag. For model B, the robust LM tests are strongly significant for spatial lag dependence, and moderately significant for spatial error dependence. Thus, a spatial lag model is constructed for model A, and a spatial lag and combined spatial lag and error model for model B.

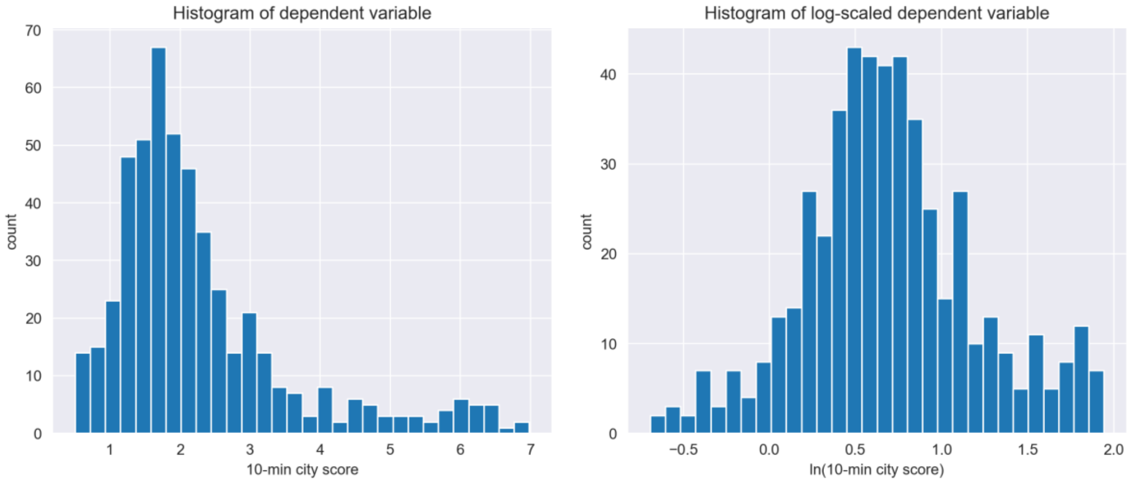


***Figure 12:*** *dependent variable (left) before log-scaling and (right) after log-scaling, as used in the models*

Table 6 presents the results of the lag models for model A and B, with the $CS_{10}$ excluding jobs as the DV. The combination model, and models with the $CS_{10}$ including jobs are presented in Appendix E.8.

***Table 6:*** *Spatial regression results, DV = $CS_{10}$ without jobs*

| | **Model A (indicator-based)** | | **Model B** | |
|---|---|---|---|---|
| | **Lag (w = Rook)** | | **Lag (w = Rook)** | |
| **Variables** | **Coefficient** | **Standard error** | **Coefficient** | **Standard error** |
| Constant | 0.201*** | 0.041 | 0.096* | 0.046 |
| % soc. minimum | 0.014*** | 0.004 | 0.005 | 0.005 |
| % welfare | 0.394** | 0.148 | 0.302* | 0.151 |
| % > 65 years | -0.034 | 0.097 | 0.045 | 0.099 |
| % < 15 years | -0.520*** | 0.121 | -0.369** | 0.140 |
| % immigrants | -0.112 | 0.073 | -0.157* | 0.075 |
| D train station | -0.043*** | 0.010 | -0.028** | 0.010 |
| % < 1945 | | | 0.010*** | 0.003 |
| % > 1994 | | | 0.006* | 0.003 |
| % apartments | | | 0.075* | 0.036 |
| Income | | | 0.005 | 0.073 |
| Pop. density | | | 0.083*** | 0.025 |
| Rho (lag) | 1.446*** | 1.467 | 1.384*** | 1.658 |
| Lambda (error) | | | | |
| **Spatial dependency residuals** | | | | |
| Global Moran's I z-value, p-value | 1.323 | 0.186 | 1.201 | 0.230 |
| **Model fit** | | | | |
| LL | 113.90 | | 135.69 | |
| AIC | -211.79 | | -245.38 | |
| R2 | 0.362 | | 0.488 | |

*** = P < 0.001; ** = P <0.01; * = P <0.05

The spatial weights matrix for the models is chosen from the three spatial weights matrices based on the best model fit and least statically significant Moran's I value of the residuals. The spatial lag models both have a higher log likelihood and lower AIC value than in their OLS counterparts, indicating a better model fit of the spatial model. Thus, the spatial models are considered better for interpreting relationship of the explanatory variables with the $CS_{10}$. Furthermore, the residuals of both models are not significantly clustered according to the Moran's I statistic and can be seen in Appendix E.9.

In model A, the same explanatory variables are statistically significant as in the OLS model, with the addition of the variable of percentage of people receiving welfare money now having moderate evidence of a positive relationship with the value of the $CS_{10}$. The other significant variables have somewhat the same effect, but smaller. The spatial lag effect (ρ) is positive and statistically significant, suggesting a spatial spill over effect. The value of the $CS_{10}$ in a grid cell increases by 1.45% for each percentage point increase in the $CS_{10}$ in its direct neighbours (Rook case).

In model B, the same explanatory variables are statistically significant as in the OLS model, with the addition of the variables for percentage of people receiving welfare money, and the percentage of people with immigration background. There is moderate evidence for the percentage of people with immigration background living in a grid cell having a negative relationship with the value of the metric. For each percent increase in the percentage of people with immigration background, the value of the metric decreases with 0.16%. A 1% increase in people receiving welfare is related to a 0.302% increase in the metric. Furthermore, the percentage of houses constructed after 1994 in the OLS model had a small negative relation with the metric, but in the spatial lag model has a slightly positive relationship with the metric. All other significant explanatory variables have a smaller effect in the spatial lag model than in the OLS model. Lastly, the spatial lag effect (ρ) is positive and statistically significant, suggesting a spatial spill over effect. The value of the $CS_{10}$ in a grid cell increases by 1.38% for each percentage increase in the $CS_{10}$ in its direct neighbours (Rook case).

Finally, the combined spatial lag and error model (Appendix E.8) does not perform as well as the spatial lag model for the variables in model B. Only percentage of people over 65 years, percentage of people on welfare, houses built after 1994, and population density have evidence of a statistically significant positive relationship with the $CS_{10}$. The spatial lag coefficient is positive and significant, but the spatial error coefficient is negative. This suggests that while there is a spill-over effect in the $CS_{10}$, there is also an effect caused by unobserved variables, causing the error terms to be negatively associated between neighbouring cells.

When accessibility to jobs is included in the score, the percentage of people receiving welfare has a stronger positive relationship with the $CS_{10}$, compared to when jobs are not included. Thus, these people – often looking for jobs – do have accessibility to jobs, although it is not clear from the data if these are the right jobs (matching). The percentage of people with immigration background still has a negative relationship with the $CS_{10}$ in this case, but slightly less so. Furthermore, the factor for density is slightly lower, but still positive, and the percentage of apartments is not significant anymore. However, overall, including jobs in the DV does not make a significant difference in results of the spatial regression.

The model with more variables has a lower spatial lag effect (1.38 compared to 1.45), but this difference is marginal. Thus, the extra variables capture some of the spatial variance of the metric, but not all. This makes sense because the value of the metric is heavily influenced by location and the values are highly clustered (see Table 5).

### *5.4 Scenario analysis*

Results of the metric in the tested scenario can be found in appendix E.10. **Figure 13** shows the difference between the tested scenario and the base scenario. While $CS_{10}$ is higher in the city centre in scenario 1 than in the base scenario, maximum score (found in Bunnik) is slightly lower than in the base scenario for the 10-minute threshold. However, in the 15-minute analysis the maximum score is higher in the scenario with new cycling connections. **Figure 13** also shows that while scores increase in the city centre, they decrease slightly in the areas around the city centre. This difference is most notable in the $CS_{10}$, where the score decreases right around the city centre as a result of increased demand due to the new connections. The population density in this area is somewhat higher than in the city centre. The $CS_{10}$ increases in scenario 1 for 45.8% of the population, and decreases for 45.2% of the population. For 15 minutes, it increases for 45.6% and decreases for 50.6% of the population. However, it should be noted that for both thresholds, in around 80% of grid cells the change in score is very small (between -0.02 and +0.02).

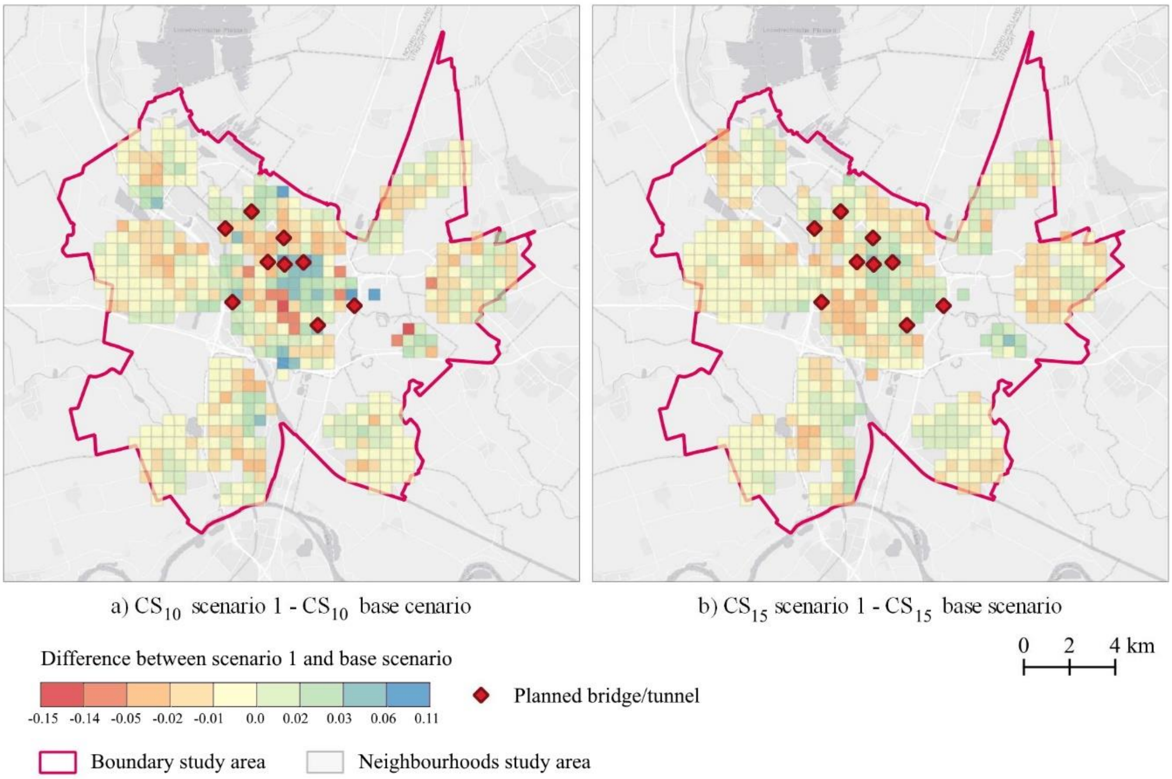


***Figure 13:*** *Change in $CS_{10}$ and $CS_{15}$ with scenario 1*

Table 7 shows that the average $CS_{10}$ in scenario 1 increases only marginally despite the new cycling connections. For the 15-minute threshold, the average value decreases an exceedingly small amount. This is a result of demand that increases as well as the supply. When more services can be reached from a grid cell because of a new connection, these services could possibly also be reached by more people from other grid cells, thus increasing the demand side of the methodology used. Because of this, the overall scores do not differ much between the base scenario and scenario 1. However, slightly more people live in a 10-minute city as a result of the new connections.

***Table 7:*** *Population in x-minute city, average, median, and maximum $CS_x$ in different scenarios*

| Case | % pop CSx > 0 | Average $CS_x$ | Median $CS_x$ | Maximum $CS_x$ |
|---|---|---|---|---|
| $CS_{10}$ base scenario | 94.24 | 0.185 | 0.162 | 0.669 |
| $CS_{10}$ scenario 1 | 94.28 | 0.186 | 0.161 | 0.565 |
| $CS_{15}$ base scenario | 99.97 | 0.197 | 0.176 | 0.449 |
| $CS_{15}$ scenario 1 | 99.97 | 0.196 | 0.175 | 0.470 |

## 6. Discussion

### *6.1 Interpretation of results*

The $CS_{10}$ and $CS_{15}$ in the study area show that while not every location is a 10-minute city, almost every location is a 15-minute city, where at least one of each service type can be reached within a 15-minute bike ride. However, this does not take into account threshold values for amount of a type of service needed for the population (capacity), and some areas only minimally fulfil the requirements. Also differences between the city centre of Utrecht and the surrounding periphery and towns are large. These differences are even larger in the $CS_{10}$ than the $CS_{15}$, which shows slightly more homogeneous results.

The more heterogeneous results of the $CS_{10}$ and the difference between the $CS_{10}$ and $CS_{15}$ together provide insights into the current status of the study area as a 10- and 15-minute city. Because the scores around the city centre of Utrecht (and towards the edges of the suburbs) are generally lower when travel time is lower, people living in these areas have to travel further to find the same number of opportunities as someone living in the city centre. Residents in the city centre of Utrecht and the cores of the surrounding towns benefit from the lower travel time, providing demand is also within this lower travel time. thus, people living in these centres would also benefit if the other areas score higher as a 10- or 15-minute city, i.e., if the overall results are more homogeneous.

Because of the use of supply and demand in the metric, small towns such as Bunnik with a lower number of services but also a lower number of residents can be compared to a city such as Utrecht. It also shows that Bunnik scores relatively high in the study area, and benefits from its island like form. Especially with the 10-minute threshold, demand for the services located in Bunnik is only from residents living in Bunnik and not from Zeist, from where people can reach Bunnik within 15-minutes cycling.

The sensitivity analysis on the weights of the metric shows that results are still quite uncertain and heavily influenced by the weights. Variance in the output value of the metric is quite large. Results show that especially the weights for entertainment, recreation, and jobs are quite uncertain. Recreation and entertainment were weighed quite low, and jobs was weighed the highest. This sensitivity analysis shows that the metric might benefit from trying different weighting schemes, and not basing conclusions on an urban area's status as a 15-minute city on only one type of weighting scheme. Future research can employ surveys among residents to derive other weighing schemes. The sensitivity analysis also shows that it remains important to be able to look into the different destination types and their individual scores, as well as different weighing schemes for different socio-demographic groups.

Spatial regression has shown that, as expected, there is spatial dependency in the $CS_{10}$. The spatial models perform a lot better because the dependent variable is heavily influenced by location and the services in the vicinity. Neighbouring grid cells share many of the same services that are accessible to people and thus their scores are similar. However, the spatial models also show that people on welfare and people with low income generally do not have a lower accessibility to the services in the 15-minute city in the study area, contradictory to the expectations following from the transport poverty literature (Jorritsma et al., 2018; Kampert et al., 2018). This, however, does reinforce the notion that the 15-minute city and cycling specifically, can aid in reaching transport equity, where the same opportunities are accessible for everyone.

On the other hand, people with immigration background (who were born outside of the Netherlands or whose parents were born outside of the Netherlands) tend to live more in neighbourhoods where the $CS_{10}$ is lower. This may indicate a disadvantage for people with immigration background with relation to having opportunity to live in a neighbourhood where more services are accessible. It should be noted that people with immigration background generally have a lower cycling trip rate than people without immigration background in the Netherlands (CBS, 2021), but this could not be concluded from the NVP data for the study area itself. (Nello-Deakin & Harms, 2019) found that regardless of environmental characteristics such as access to services, people with immigration background cycle less. Thus, a higher $CS_{10}$ may not incentivize these people to cycle more, and perhaps other nudging schemes are more effective. However, the availability of services within range remains important for everyone.

People with children (under 15 years) also tend to live in neighbourhoods where the $CS_{10}$ is lower. While this study does not make it clear if people with children choose to live in quieter neighbourhoods, the study area mostly consists of very urban neighbourhoods. Families with children also tend to live more in single family houses instead of apartments; there is a negative correlation between percentage of multifamily buildings and percentage of children of -0.36. Children are highly dependent on bike-ability and walkability of their place of residence to achieve independence at an early age, and they might benefit from having services such as schools, sport clubs, and recreation being more accessible.

Furthermore, including physical characteristics of neighbourhoods in the model shows that more dense neighbourhoods with older houses, which are apartments instead of single-family homes tend to have a higher $CS_{10}$. Houses built after 1994, when the Netherlands started building the VINEX neighbourhoods (Min. VROM, 1991), first seem to have a negative relation to the $CS_{10}$, but when accounting for spatial lag, they have a small positive relation to the $CS_{10}$. Thus, it can be concluded that when accounting for spatial lag, the era in which a house was built matters less, since both before 1945 and 1994 have a positive relation to the $CS_{10}$.

Lastly, the spatial lag coefficient is quite high in both models. There may be many other neighbourhood characteristic variables such as length of bike path in a grid cell that can explain more of the $CS_{10}$ in a spatial model. Such variables were not included in this study but should be investigated in future research.

## *6.2 Practical implications*

Results of the mobility analysis show that people in urbanised areas in the Netherlands bike on average around 10 to 15 minutes to different destinations. Distance decay functions and analysis also show people are willing to bike 10 to 15 minutes to most of the destination types before the function (and willingness) starts to drop. 10 to 15 minutes may thus be a good threshold for the x-minute cycling city in the Netherlands. Additionally, with the increasing popularity of e-bikes, some destination types do not need to be present within the 15-minute shed. However, some destination types such as food should perhaps be accessible in under 5 minutes. Also, people may prefer to walk to certain destination types but this requires more analysis.

Since many people in urbanised areas already bike around 15 minutes to their destinations, a lot of places in the Netherlands are arguably already a 15-minute city. However, choice of mode related to travel time or distance was not investigated in this study, and it may be that people find their destinations further away but choose a different mode such as the car or public transit. In conclusion, a widespread classification of Dutch cities as a 15-minute city cannot directly be concluded from the mobility analysis. Instead, proximity analysis in combination with mobility analysis is necessary to conclude if a place is a 15-minute city.

However, generally Dutch cities are not as large and sprawling as for example North American cities and thus many people can easily reach the centre of the town or city where they reside. For improvements in cities, focus in the Netherlands may be on neighbourhoods that score relatively low. Increasing liveability and livelihood in these neighbourhoods may benefit all.

The methodology and case study show that the city of Utrecht itself is a 10- and 15-minute city for cycling, albeit some neighbourhoods scoring substantially higher than others. All surrounding towns are also 15-minute cities, but not all places are a 10-minute city. Some services are simply not available within 10 minutes cycling for everyone. An analysis focused on walking may reveal that Utrecht itself is also not a 10-minute (walking) city, but this should be investigated in further research.

The destination types that are inaccessible in some places within 10 minutes cycling are important ones as well; healthcare and sports, and entertainment to some degree, which is the case in the south of Houten. Arguably, these are some of the most important destination types, especially healthcare, since frequent users such as elderly may be unable to bike (or walk) very far.

The mobility and uncertainty analysis show that especially the recreation category is difficult to capture. Destinations in this category are hard to define (besides the playgrounds and parks) because a recreational bike ride or walk does not always have a destination. To capture the recreational qualities of a neighbourhood in a 15-minute city, assessment of attractiveness, number of green/blue features, and other quality improving factors, such as places to sit may improve the completeness of the methodology. This can be quantified on one hand through more data (canopy coverage, grass coverage, number of benches), and on the other hand through surveys gauging residential satisfaction regarding physical condition of the neighbourhood.

Practitioners agreed that the metric was interpretable and understandable, including the supply and demand sides that were both taken into account. This aspect of the accessibility measures chosen was appreciated because the city centre did not score the highest on everything, and it spoke to the experts. In that way, the results shown lined up with their real-world expectation and knowledge of the study area.

Improvements to the 10- or 15-minute city scores in the city of Utrecht may come from focusing on the lower scoring neighbourhoods such as Overvecht, Zuilen Noord, Kanaleneiland, and Vleuten-De Meern. Economic and policy stimulation of more small stores, restaurants, and other leisure activities in neighbourhoods may alleviate pressure from the city centre as well as improve the score in these neighbourhoods. Recent city council elections in Utrecht showed that there is interest for such schemes among the political parties (Bij1 Utrecht, 2022; D66 Utrecht, 2021; PvdA Utrecht, 2022), but practical implementation is key. To achieve these ambitions, the $CS_x$ can help pinpoint areas to focus efforts on. Improvements in the surrounding towns may come from focusing not only on the cores but also the fringes, implementing new services in newly developed or developing neighbourhoods, and better cycling connections to the cores of the towns.

The methodology described in this study is suitable for simulating network improvements and testing scenarios. A scenario with somewhat improved cycling connections showed no significant changes in the score, aside from a small increase in the city centre. A small increase in population living in a 10-minute city (with at least one service of each type accessible) was observed as a result of the added cycling connections. The metric can be used to evaluate scenarios like this and select best options or prioritise projects that would be most beneficial for residents. The scenario analysis showed that not every new connection leads to an increase in the metric value in all grid cells, due to increased demand. New connections can be prioritised based on the net increase in $CS_x$ they provide.

Additionally, new housing developments can be evaluated as well as increasing density through housing in already existing neighbourhoods. Assessments can then be made towards the 10- or 15-minute city score. Ideally, the score would not decline in locations neighbouring the new development from increased demand but stay the same or improve as a result of equally increased service provision.

### 6.3 Limitations and further research

There are some limitations to this study. First of all, because travel data from the Netherlands was used to determine input characteristics, the metric may not be transferable to other countries. Although the methodology is transferable, the input characteristics are most likely not, because Dutch people cycle a lot. Furthermore, the metric and case study here only deal with cycling and not with walking, as is specified as a mode for the 15-minute city. There was also no distinction made for e-bikes, although e-bikes mostly serve a different purpose (replacing car trips up to 20 km), and do not necessarily have to be the focus in a 15-minute city. The accessibility analysis does not consider quality and safety of the cycling network in this study, but these factors may impact the experienced travel time. Also, the bike network was simplified by applying an average speed of 15 km/h on all roads. Thus, speed is only influenced by the wait time at the intersections included in the network and not by personal characteristics or (cycling) traffic intensities. Accessibility was only calculated for the shortest route, while study shows that not everyone chooses the shortest route every time (Bernardi et al., 2018). Finally, including capacity and quality of services will provide more nuance and details in the results, but these factors were not available in the data used in this study. As mentioned in section 6.2, further including attractiveness of the built environment, number of green/blue features, and other quality improving factors may improve the completeness of the methodology.

While practitioners found the metric interpretable and understandable because of the supply and demand side that were both taken into account, possible future research directions were defined regarding including the capacity of services, diversity measures for restaurants and shops, and quality of the network. Expanding the metric with walking accessibility scores may lead to more nuanced conclusions about a city. Walking as well as cycling should be included, since some people that are unable to bike or use a similar mode of transport are able to walk. Other than that, including walking may provide more nuanced results with regards to people that bike relatively slow.

Different weighing schemes should be investigated. This study used a weighing scheme derived from the NVP recorded travel data, which has as a disadvantage that they only capture what people are able to do and currently do, and not what they want to do (preference). Although practitioners agreed that the destination types and their weights show what is possible with the metric, suggestions were made to base weights more on peoples' preferences through surveys. In the 15-minute city, all six service categories as defined by Moreno are important to be present within the threshold. However, some person might find having bars and restaurants close to their place of residence more important than having a large park close to their house, while the opposite is true for another; this is personal taste and preference and best analysed through surveys (stated preference) such as in (Weng et al., 2019). Weng et al. (2019) used a survey among residents of different ages to rank different destinations in order of importance. The rankings and weights found here were quite different from those of the NVP, especially for healthcare since people do not go there often, but they like to have it in close proximity to their home. Furthermore, the weights were very different for recreation. Using a weighting scheme based on a survey in the Netherlands may yield different results, as it was shown in the sensitivity analysis that the uncertainty in the output due to the weights is in some cases quite large.

Lastly, in order to fully conclude if a place is a 15-minute city, services need to be available, but also visited (mostly) by the people that live close to them (Graells-Garrido et al., 2021). The 15-minute city metric together with a mobility analysis applied in the same area can thus provide insights to conclude if a place is really a 15-minute city or not.

## 7. Conclusion

The aim of this study was to develop a metric to assess 15-minute cities based on cycling accessibility measures, and assess whether the city of Utrecht and its surrounding towns is a 15-minute or 10-minute city. This was done using recorded travel data and 2SFCA accessibility measures. The status of Utrecht as a 10-minute city was further investigated using spatial regression. To conclude this research, the research questions are answered one by one.

*What is a 15-minute city and which services should be present?*

The number and type of services in the 15-minute city are not universally agreed upon, with different studies using different definitions and destination types. In this study, nine destination types were defined, which is more than the original 5 (6 including housing) defined by Carlos Moreno. While bars and restaurants, entertainment venues, sports venues, and recreational areas are all grouped in the entertainment category in this original definition, this study defined them as separate destination types, thus capturing some of the diversity dimension in the accessibility scores. The same is true for destination types food and commercial (originally commerce).

Descriptive statistics of the mobility analysis shows that people in the Netherlands (still) most frequently travel to work, while recreational trips often do not have a specific destination and may be better quantified by looking at neighbourhood characteristics and their qualities. To conclude, the 15-minute city is different for everyone else, depending on one's preferences and lifestyle, but should universally include food, job opportunities, entertainment and recreation, green spaces, commercial destinations, and healthcare. Other than that, definition of the 15-minute city can be modified to fit the culture of the location under study and its inhabitants. The developed methodology allows for modification of the weights of the destination types, as well as the distance decay functions.

*What mobility patterns can be derived from recorded travel data of different socio-demographic groups cycling in urbanised areas in the Netherlands?*

Descriptive statistics from the NVP data show that Dutch people in urbanised areas cycle around 12 minutes on average to any destination. Fitted distance decay function show that people tend to cycle further to the office and for recreation than to other destination types. Distinguishing between age groups shows distinct patterns for younger people travelling further to school, recreation, and sports, while older people cycle further to healthcare and bars and restaurants. While the influence of trip length (and other factors) on mode choice were not investigated in this study, the recorded cycling trips show that a trip duration of up to 15 minutes fits well within the Dutch cycling context and thus the x-minute city.

The number of bicycle trips per person per day differs most between household types, where people in households with children bike more than people in household without children. People aged over 65 years make fewer cycling trips per day than people aged under 65 years.

*To what extent do accessibility levels of different services in the study area establish the area as a 15-minute and a 10-minute city?*

The results of the metric show that the study area is a 15-minute city for 99.9% of population within the area, and a 10-minute city for 94% of the population in the study area, with at least one service of each destination type accessible within 10 minutes cycling. Thus, it can be concluded that a very high percentage of the population in the study area lives in a 15- and even 10-minute city. Although, both the $CS_{15}$ and $CS_{10}$ are quite low in some areas outside of the city centre and the town cores and barely meet the definition of one service per destination type accessible.

The bivariate local Moran's I of the metric and its standard deviation show that there are some areas that score high but also have high standard deviation and thus need improvements in some service categories. Other neighbourhoods where $CS_x$ is high and standard deviation is low may serve as examples of good practice for the 15-minute city, such as in Zeist, Maarssen, and Bilthoven. These neighbourhoods do not necessarily have the highest absolute values for the $CS_{10}$ and $CS_{15}$, but provide a sufficient mix of destination types accessible within low cycling travel times.

*To what extent are socio-demographic and physical neighbourhood characteristics correlated with the metric and what are the spatial inequalities in the 10-minute city?*

Bivariate local Moran's I of the metric result and different socio-demographic characteristics show a clear relationship between the percentage of children in a neighbourhood and the $CS_{10}$. While many families with children live in Vleuten-De Meern, the score is low in this neighbourhood. Although, it should be noted that weighing of the destination types might by quite different for families with children than the average weights of the entire NVP dataset that were used, that prioritise access to schools, playgrounds, and parks. Also, there are spatial inequalities between neighbourhoods. Overvecht is a neighbourhood where relatively many socially and economically disadvantaged people live, and they have low accessibility levels to services in the 10-minute city. However, Kanaleneiland is another example of a neighbourhood with residents that are socially and economically disadvantaged, but accessibility levels are higher. These bivariate local Moran's I results can serve to indicate good practice neighbourhoods, where transport equality is better.

Spatial regression showed that some factors such as building age, building type, percentage of people with immigration background, and percentage of children are correlated to the $CS_{10}$. Population density is heavily correlated with the $CS_{10}$, showing that high density is especially important for accessibility of all services, and is indicated as one of the dimensions of the 15-minute city (Moreno et al., 2021). The spatial regression in this study shows that it might be the most important physical characteristic of neighbourhoods in the 10- (or 15) minute city, together with multifamily buildings instead of single-family ones.

Furthermore, while percentage of people receiving welfare has a positive correlation with the $CS_{10}$, percentage of people with immigration background and percentage of children have strong negative relationships with the $CS_{10}$. These groups are both disadvantaged with regards to the areas where they live having a lower accessibility to opportunities within 10 minutes.

*What is the effect of transportation measures on the metric?*

Scenario analysis shows that improvement of the $CS_x$ is not as straightforward with a net positive increase as a result of new connections. While some areas benefit from new connections, in other the $CS_x$ decreases as a result of increased demand simultaneously with increased accessibility using the new connections. This is especially true for areas right around the city centre of Utrecht, where population density is high. However, overall as a result of the new connections, the $CS_{10}$ improves for most people, and percentage of the population living in a 10-minute city increases as well. The methodology can be used to evaluate scenarios. Because both supply and demand are taken into account, the methodology is also suitable for measuring the effect of new neighbourhoods or developments on the $CS_x$.

The main objective of this study was to develop a metric for 15-minute cities and apply this in a case study. An aggregated metric of gravity-based 2SFCA accessibility measures for nine different destination types was developed for this purpose. The results of the metric in the study area provide insights into the progress towards becoming a 15-minute city, and reveal problematic areas that may be prioritised to improve the score. Applying spatial clustering techniques can yield more insight into good practice areas, and areas that need improvements in some categories. To pinpoint problematic service categories however, one should always look beyond a composite indicator to the underlying sub indicators for more nuanced discussion. Tools like this can help cities on their way to become a 15-minute or 10-minute city, while measures for improvement can also be evaluated in order to select the best or most efficient one.

This research is the first where cycling accessibility measures are combined to quantify the 15-minute city, and scrutinize a study area with regards to the concept. A combination with walking, and a mobility analysis in the area under study can provide further nuanced insights to assess the location as a 15-minute city and pinpoint problematic aspects or areas where efforts of improvement should be focused.

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