A composite X-minute city cycling accessibility metric and its role in assessing spatial and socioeconomic inequalities – A case study in Utrecht, the Netherlands

Elizabeth Knap, Mehmet Baran Ulak, Karst T. Geurs, Alex Mulders, Sander van der Drift

A R T I C L E   I N F O

Keywords: X-minute city metric 2SFCA approach Cycling transport equity Spatial regression

A B S T R A C T

The 15 min city (or “X-minute city” in general) concept aims to give people access to all essential services and daily needs (e.g., healthcare, education, etc.) within X minutes of active transportation, to improve transport equity, sustainability, and traffic safety. To date, there is a lack of methods and tools to assess to what degree cities currently, or after implementing policies, comply with the X-minute city concept. This research aims to develop a methodology for quantifying the X-minute city through a metric (CSx) that was developed based on an accessibility framework and tested for cycling mode in the Utrecht region in the Netherlands as a study area. Travel data from the Netherlands mobility panel were analysed to determine input characteristics of the metric, such as the weight of destination types. Standardized gravity-based 2-step floating catchment area (2SFCA) accessibility scores for all destination types were weighted and aggregated into a composite metric that shows relative scores as an X-minute city. The results of the analysis show that 100% of the population in the Utrecht region has access to at least one destination for all 9 destination types within 15 min, whereas this number reduces to 94% within a 10 min cycling threshold; indicating the status of Utrecht as a cycling city with cycling-friendly infrastructure. Furthermore, low-income groups do not have lower cycling accessibility to the services in the 15 min city in the study area, reinforcing the notion that cycling can be an effective solution to reduce transport inequalities. The developed metric can be used to assess cities on their way towards becoming X-minute city, prioritise neighbourhoods to develop, set quantifiable goals, and evaluate planning scenarios.

1. Introduction

Urban population is increasing all over the world and this increase causes 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 and crashes, coupled with polluted air and a diminished environment in cities. Covid-19 lockdowns showed that it is possible to improve the overall urban quality by decreasing motorised-vehicle travel in cities (Albayati et al., 2021; Goenaga et al., 2021; Liu & Stern, 2021; van der Drift et al., 2021; Wang & Li, 2021). However, the lockdowns also exposed 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 min city (or “X-minute city” in general), a concept first defined by Carlos Moreno in 2015 and discussed in more detail in Moreno et al. (2021), gained popularity during the pandemic. The concept’s goal is to give people access to all essential services and daily needs (e.g., healthcare, education, etc.) within X minutes of active transportation (walking, cycling), thus reducing traffic demand, overall time spent in traffic, congestion, and pollution. Note that the early X-minute city concept as developed by Moreno focuses on proximity to basic amenities and public transport is not included. Others have excluded public transport as public transport travel times depend on external factors such as delays and access/egress connections (Duany & Steuteville, 2021).

Services that may be included in the X-minute city encompass public schools, parks, libraries, grocery stores, retail, employment places, basic healthcare, and places for entertainment or recreation. The concept is proposed to create lively and liveable neighbourhoods, promote economic growth, support social cohesion and sustainability (Moreno et al., 2021), and improve the health and well-being of residents (Boulange et al., 2017; Gao et al., 2020; Riggs & Sethi, 2019; Weng et al., 2019). Advocates of the concept argue that the X-minute cities are a potent solution for encouraging deep decarbonisation.

* Corresponding author.
E-mail address: m.b.ulak@utwente.nl (M.B. Ulak).

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(Allam et al., 2022) and that it contributes to building safer, more re-
silient, sustainable and inclusive cities, as depicted in the Sustainable
Development Goal 11 of the United Nations (Moreno et al., 2021). The
X-minute city can help to mitigate the impacts of societal shocks such
as Covid-19 and fuel price fluctuations as its residents are less reliant on
motorised transport to fulfil their daily needs.

Several cities around the world such as Paris, Barcelona, Melbourne,
Portland, Shanghai, and more are now adjusting their transport policies
to fit the X-minute city concept (Pozoukidou & Chatziyiannaki, 2021).
Implementation of the 15 min city concept not only calls for walkability
and safe bicycle infrastructure, but also mixed land use, appropriate
density, and adequate spatial distribution of services, commerce, and
green spaces. The 15 min city can be a possible solution in urban plan-
nig to reduce energy use in cities and reduce emissions to mitigate cli-
mate change (IPCC, 2022). In the Netherlands, Utrecht is the first city
that has stated they want to become a 10 min city with services such as
healthcare, sports, education, shopping, and more within a 10 min walk
or bike ride from people’s homes. Although several neighbourhoods in
Dutch cities might already meet some of the requirements of 15 min
cities, these requirements have never been quantified nor measured.

Literature on the 15 min city introduced and defined the concept
(Moreno et al., 2021); reviewed city plans for becoming a 15 min city
(Pozoukidou & Chatziyiannaki, 2021); measured neighbourhood char-
acteristics and travel behaviour (Carpio-Pinedo et al., 2021; Gaxiola-
Beltrán et al., 2021; Graells-Garrido et al., 2021; Weng et al., 2019); and
measured the potential for the 15 min by walking (Abdel fattah et al.,
2022; Caselli et al., 2021). This paper addresses three knowledge gaps
in the literature. First, the concept of the X-minute city has been qual-
titatively defined and interpreted in many studies, but much less research
has been done on how to measure the concept using accessibility met-
rics. Second, existing quantitative studies have focused on the role of
walking in the X–minute city (e.g., Ferrer-Ortiz et al. 2022). The role of
cycling has received less attention, whereas cycling is one of the main
modes of transport in Dutch cities. Third, there is scarce research on
how X-minute city scores vary across socio-demographic groups at the
neighbourhood level within cities. Therefore, this study aims to develop
a composite metric to assess X-minute cities based on cycling accessibil-
ity measures, and assess the spatial and sociodemographic inequalities
with regard to X-minute city scores of neighbourhoods in Utrecht and
its surrounding towns in the Netherlands.

To achieve the objectives of the study, first, recorded travel data
were used to determine mobility patterns, appropriate cycling distances,
and the frequency of different daily activities in urbanised areas in the
Netherlands. Then, the set of candidate services to be included in the
calculation of the X-minute city metric was identified and the resultant
metric was calculated. Finally, spatial and socio-demographic inequal-
ities were investigated based on the current physical neighbourhood
characteristics and the impacts of future transportation investments and
changes on the X-minute city were assessed in two scenario analyses.
Although the concept of the X-minute city concept considers all active
transportation modes, only cycling was utilized in the development of
the metric.

2. Literature review

2.1. Quantification of the X-minute city

Although the name of the concept suggests a straightforward and
quantitative nature, there are many variations in the quantification of
the metric such as using different threshold travel times and alter-
native modes (i.e., public transport). That is, the X-minute city
has been adapted to fit different regional needs, such as 20 min
neighbourhoods in Melbourne (Melbourne Government, 2017) and
Portland (Portland, 2010), the 15 min city in Paris (Paris en Com-
mun, 2020), and now the ambition of Utrecht for the 10 min city
(Gemeente Utrecht, 2019). Furthermore, the types of services included
in the development of X-minute city metrics differ drastically be-
tween plans and in the literature (Carpio-Pinedo et al., 2021; Gaxiola-
Beltrán et al., 2021; Graells-Garrido et al., 2021; Moreno et al., 2021).
In summary, the X-minute travel time is not rigid and can be adjusted
in different cases or contexts (Duany & Steuteville, 2021).

The Netherlands is amongst the highest cycling countries and its
cities are amongst the highest cycling cities across the globe (Goel et al.,
2021). This dominance of cycling over walking makes the concept of
X-minute cities in the Dutch context different from most other countries.
Thus, this research focuses only on cycling and cycling accessibility.

2.2. Services in the X-minute city

Moreno et al. (2021) state that six main categories should be included
in X-minute city quantification: living, working, commerce, healthcare,
education, and entertainment. Graells-
Garrido et al. (2021) add access to healthy food, government facilities,
green spaces, and public transit to this list. Furthermore, green spaces
in cities are important considering the effects of climate change and urban
heat islands. Table 1 presents the services considered by literature
that either define the X-minute city concept or use it in analysis or
assessment.

The six main categories seem to be present in some way in most of
the literature (Moreno et al., 2021). Employment is an important char-
acteristic of the X-minute city because most workers commute to work
each day. In the Netherlands, two-thirds of short-distance commuting
trips (0-5 kilometres corresponding to 0-20 min based on 15 km/h av-
average cycling speed) are done on foot or by bike, with the bicycle as the
most important mode (55% mode share) (de Haas & Hamersma, 2020).

<table>
<thead>
<tr>
<th>Source</th>
<th>Services</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moreno et al., 2021</td>
<td>Categories: Living, Working, Commerce, Healthcare, Education, Entertainment 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)</td>
<td>Definition</td>
</tr>
<tr>
<td>Weng et al., 2019</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pozoukidou &amp; Chatziyiannaki, 2021</td>
<td>Categories: Work, Basic healthcare, Cultural and recreational opportunities, “key resources”</td>
<td></td>
</tr>
<tr>
<td>Carpio-Pinedo et al., 2021</td>
<td>Land-use types: Industrial, Offices, Commercial, Sports, Show business, Leisure and hospitality, Health, Cultural, Religious 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)</td>
<td></td>
</tr>
<tr>
<td>Gaxiola-Beltrán et al., 2021</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1 presents the services considered by papers that either define the 15 min city concept or use it in analysis or assessment. The living category is captured by the origin points and spatial unit used in the analysis, and the housing affordability category in Pozoukidou and Chatziyiannaki (2021). The working category is considered in Carpio-Pinedo et al. (2021) and Pozoukidou and 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 a distinction in size (number of job positions). The commerce category is included in all other studies but in different ways. Gaxiola-Beltrán et al. (2021) only include supermarkets, which provide the most essential of daily needs, while 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 hospitals, pharmacies, or general practitioners. 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 min 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. 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.

2.3. Accessibility measures for active transportation

Different types of accessibility measures, such as distance-based, gravity-based, infrastructure-based, and Walk Score types are available (Vale et al., 2016). Distance-based measures only consider the travel time or distance from an origin to a destination within a threshold. These measures are relatively simple to compute but the distance threshold is arbitrarily chosen and may have a large influence on the number of opportunities that can be reached. Gravity-based measures, on the other hand, assign weights to opportunities based on their distance or travel time from the origin point, and possibly other factors such as floor space, or the number of employees (El-Geneid & Manauth, 2012; Kockelman, 1997). These measures are more realistic because destinations further away are less attractive than closer ones. The Shen index (1998) and its equivalent the two-step floating catchment area method (2SFCA) (Luo & Wang, 2003) combine two potential accessibility measures to into account the supply and demand of service. The enhanced 2SFCA index provides a ratio between the accessible opportunities and the population that can reach said opportunities using a decay or impedance function for both. It is a straightforward accessibility indicator to include competition effects into accessibility analysis. It is often used to measure accessibility to healthcare or other service providers with capacity constraints. The inclusion of competition effects is also relevant for measuring job accessibility and can reveal different spatial patterns and equity impacts than a standard potential accessibility measure (e.g., Cervero et al. 1995, Geurs & Eck 2003, Pritchard et al. 2019, Shen 1998). In this paper, including competition effects is particularly relevant as the spatial distribution of jobs (supply) at walking or cycling distance can be very different from the spatial distribution of workers (demand). Furthermore, the 2SFCA approach has also been used to examine disparities or inequalities in the distribution of urban parks and green spaces (Domy et al., 2015). In this paper, we apply the same accessibility index to all destinations to achieve consistent scores and allow comparisons between destinations.

Lastly, some composite measures such as Bike Score (Winters et al., 2013) which is based on Walk Score 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. Other walkability and bikeability indexes may include topological characteristics of the network, such as intersection count and percentage of roads with sidewalks (Vargo et al., 2012) or even go as far as to include the quality, width, and maintenance of available sidewalks, as well as the slope, number of problematic intersections, speed limit, and more (Horacek et al., 2012).

2.4. Conclusions from the literature

The concept of the X-minute city has been qualitatively defined and interpreted in other studies (Gaxiola-Beltrán et al., 2021; Graells-Garrido et al., 2021; Moreno et al., 2021). Abdelfattah et al. (2022) used Walk Score and density to map the potential for the 15 min 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 by Ferrer-Oritz et al. (2022) to different urban services was focused on walking as well and labelled Barcelona as a 15 min city. Caselli et al. (2021) also investigate the walkability to different services in a single neighbourhood. The majority of the current literature focuses on walking, whereas X-minute city based on cycling has not been thoroughly studied. Moreover, dimensions such as density and land mix, the type of services to consider, the catchment areas and capacities of different services, and the comfortable biking distances have not yet been fully quantified (Chen & Crooks, 2021). Lastly, many accessibility studies including cycling 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 X-minute city, on the other hand, is a holistic concept and cannot be properly captured by only considering one type of urban service.

3. Study area and data

3.1. Study area

This research focuses on the city of Utrecht and surrounding towns (Nieuwegein, Maarssen, Houten, Zeist, De Bilt, Bilthoven, and Bunnik) as shown in Fig. 1. These towns were chosen because they are represented in the 10 min city strategy as new or existing centres for the polycentric structure (Gemeente Utrecht, 2021). The city of Utrecht is well-known as a cycling city due to the cycling-friendly infrastructure, where 48.5% of all trips within the city of Utrecht are made by bike (in Amsterdam it is 42.6%). Furthermore, Utrecht is the first city in the Netherlands to express its ambitions to become a 10 min city

3.2. Data

Table 2 presents the data sources that are used in this study, and are described in more detail below.

3.2.1. Travel patterns

Recorded travel data from the Dutch Mobility Panel (DMP) (van der Drift et al., 2021) are used in this paper to develop the X-minute city cycling accessibility metric. The DMP started in 2019 with a panel of over 5,000 participants recruited from a large online access panel. The DMP is based on a smartphone app to collect travel data of the participants entirely GDPR proof 24/7 including background knowledge comparable with traditional repetitive household surveys (e.g. income, age, household size, residential location, gender, car ownership). Recorded travel data from the DMP were selected from all records based on several criteria. Trips were recorded between December 2019 and February 2020.
as well as June and July 2021. Only trips made by people living in urbanisation levels 1, 2, or 3 (>1000 addresses/km²) to a destination type essential to the X-minute city were selected. Nine categories of destination types were considered: jobs, education, commercial, food, bars and restaurants, sports, entertainment, recreation, and healthcare. The selected DMP 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 the removal of duplicate records, the user dataset consists of 8,214 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

For the spatial information on the region, the CBS 500-by-500 m grid was chosen since it consists of equal-sized squares, unlike the postcode polygons. A 100-by-100 m grid is also available, but too small for a study focusing on cycling, considering that 4 to 7 grid cells of 500-by-500 m can already be covered in 10 to 15 min. Note that, the average cycling distance in the Netherlands is about 4 kilometres (de Haas & Hamersma, 2020). Furthermore, the 500-by-500 m data set contains information on inhabitants such as age groups, household characteristics, gender, and income, while in the 100-by-100 m grid cell data set a lot of this data is missing due to privacy regulations. Thus, the 500-by-500 m dataset is considered the best available data set for this study. Note that for higher accuracy of the accessibility assessment, the population-weighted centroids of the cells in the 500-by-500 m grid are determined by using the mean coordinates tool in QGIS. The building types of houses or apartments in the Open Street Map (OSM) point data to increase the accuracy are used in this tool, which calculates a mean coordinate for each grid cell.

Destination data is filtered from OSM data as well. Table 3 presents the number of data points and the description of each destination type. The destination types were selected based on the assessed literature as presented in Table 1. Only general practitioners were selected as the “health service” component as they are the only health service providers addressing the daily needs of residents (except in emergencies) in the Netherlands. 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 km². Job data containing the number of jobs per building are available at the building level, in a BAG data file enriched by Dat.mobility (Table 2). The data sets for commercial, bars and restaurants, and jobs are each aggregated per grid cell with a point containing the number of facilities at the weighted centroid, based on the point locations of the activities. Note that, this aggregation was needed due to the complexity of the network analysis and may lead to slight inaccuracies. However, as the weighted centroids of locations were used, such inaccuracies are not expected to affect the overall outcome.

OSM road data was used to create the bicycle network by selecting roads with cycleway type, tertiary, living street, residential, unclassified, tracks, and secondary. Of this last one, only secondary roads with the attribute ‘both ways’ were included since one-way secondary roads in the Netherlands will usually have a separated bike path.

To address the boundary effect problem a 3 km buffer zone around the study area was created and all the destinations within this zone were also included in the analysis. This is because people living right at the edge of the study area can also travel to destinations just outside of the study area within X minutes.

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Table 2

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

4.1. X-minute city cycling accessibility metric

In this paper, a composite metric is developed that combines accessibility scores with the frequency of different destinations (through weights as derived from DMP data). The developed 15 min city cycling accessibility metric consists of built environment factors and behavioural factors. Note that, the quality of the cycling network, road safety, and barriers such as crossing large roads were not considered in the development of the metric. The behavioural factor is captured in the average speed of cyclists as determined through analysis of recorded trip data, distance decay functions (see Appendix), and frequency of visits to different destination types. The conceptual model of the metric is presented in Fig. 2.

4.2. Accessibility score per destination type by 2-step floating catchment area approach

According to Penchansky and Thomas (1981), access to service 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 (i.e., supply and demand). This is important because more densely populated areas typically have more services and larger capacities; however, there are also more people using these. Due to this capability, several studies utilize 2SFCA for measuring spatial accessibility to services (Luo & Wang, 2003; Ye et al., 2018), sports facilities (Langford et al., 2017), green spaces (Wang & Wang, 2018), and jobs (Xiao et al., 2021).

The X-minute city metric in this study consists of gravity-based 2SFCA accessibility measures that take into account the age of the residents in the area (Qiu et al., 2019). The demand for a service is calculated using the distance decay functions (see Appendix) and the fraction of the population per age group. Accessibility for grid cell i for destination type p then becomes:

\[
A_{i,p} = \frac{\sum_{j=1}^{J} S_j \cdot f(c_{ij})}{D_j}
\]

where \(A_{i,p}\) is the accessibility of cell i for destination type \(p=\{1, \ldots, P\}\) (e.g., healthcare), \(j=\{1, \ldots, J\}\) is one of the destinations of destination type \(p\), \(f(c_{ij})\) is the distance decay function for cell i to access destination \(j\), \(S_j\) is the supply in destination \(j\), and \(D_j\) is the demand \(D\) for every destination \(j\) being:

\[
D_j = \sum_{k=1}^{K} \sum_{q=1}^{Q} P_{k,q} \cdot f(c_{ij})_q
\]

where \(q=\{1, \ldots, Q\}\) are the five age groups, \(k=\{1, \ldots, K\}\) are the origin cells for the demand, and \(f(c_{ij})_q\) is the distance decay function for age group \(q\) between cell \(i\) and destination \(j\). The supply of the destination type is calculated using the distance decay function specific to each destination type. The demand \(D_j\) is calculated per age group and multiplied by 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 (e.g., 15 min). Supply is calculated for the study area and 3 km buffer zone. Demand

![Fig. 2. Conceptual model of the X-minute city cycling accessibility metric.](image)
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. Note that, for education, the demand is calculated for people aged 24 or lower only. Furthermore, for jobs, the demand is calculated only for people aged between 15 and 65. For all other destination types, demand from all age groups is considered. Consequently, 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.

4.3. Aggregation of accessibility scores for the composite X-minute city metric

To aggregate the accessibility scores obtained for each service into a composite metric, the scores are needed to be normalized first to bring them on the same scale. The min-max normalization was used as follows:

\[ X_{i,p} = \frac{A_{i,p} - \min(A_{i,p})}{\max(A_{i,p}) - \min(A_{i,p})} \]  

(3)

where \( A_{i,p} \) is the accessibility of cell i for destination type p, \( X_{i,p} \) is the normalized accessibility score of cell i for destination type p. Following the normalization, the accessibility scores were aggregated based on the frequency of trips to each destination type. The weights were derived from the trip distributions calculated based on travel patterns in the DMP dataset (Fig. 3). The final metric is then defined by the equation:

\[ CS_{X,i} = \sum_{p=1}^{P} w_{p} * X_{i,p} \]  

(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 (i.e., percentage of trips to destination type p), and \( X_{i,p} \) the normalized 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 min because no destinations were further than 130 min cycling within the study area). From here on denoted as \( CS_{10}, CS_{15}, \) and \( CS_{\infty} \).

4.4. Spatial statistics and analysis

In this study, first, an adjusted version of Local Moran’s I called bivariate Local Moran’s I (Lee, 2001; Weng et al., 2019) was used to analyse spatial relationships between calculated X-minute city metrics (\( CS_{X} \)) and socio-demographic variables. The bivariate local Moran’s I identifies statistically significant clusters of high-high observations (i.e., both metric value and socio-demographic indicator are high), low-low observations as well as high-low and low-high observations. Next, spatial regression models were applied to gain insight into the relationship between the \( CS_{X} \) and some neighbourhood and population characteristics. Spatial regression modelling was adopted due to the spatial autocorrelation and spatial dependence identified in the score of \( CS_{X} \) (Anselin, 1988). There are alternative spatial regression models such as the spatial lag model (SAR), spatial error model (SEM), and combined spatially lagged and error models (SARMA) are available in the literature. To decide the best-fitting spatial regression model, Lagrange Multiplier tests are conducted (Chi & Zhu, 2020). The \( CS_{10} \) (excluding job accessibility) was chosen as the dependent variable because Utrecht has the ambition to become a 10 min city. Note that, two \( CS_{10} \) metrics, one including job accessibility and the other excluding it, were utilized for modelling. However, the difference between the two models was negligible; thus, the \( CS_{10} \) metric excluding the job accessibility was used in the final model.

The independent variables included in the model (Model A) are based on factors indicating the risk of transport poverty according to Kampert et al. (2019) and Jorritsma et al. (2018). Transport poverty entails the inability to access locations or opportunities and a disadvantage in partaking in society as a result (Kampert et al., 2019). The second model (Model B) consists of the same variables as Model A while also controlling for the built environment characteristics which might be also influential on the X-minute city metrics. This is because without addressing built environment characteristics, the effects of socio-demographic factors could simply act as proxies rather than genuine effects. To normalize the dependent variable (\( CS_{10} \)), log-scaled values were used in the regression models by taking the natural logarithm of the \( CS_{10} \). Correlations between candidate independent variables were checked to avoid multicollinearity in the models. The variables that are included in the analyses are listed below in Table 4.

4.4.1. Spatial regression modelling

A spatial regression model is similar to a standard linear model but includes a spatial lag and/or error components introducing an autoregressive effect into the model. Thus, the prediction at a location is influenced by the dependent variable values of its neighbours, as specified

**Table 4**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>% soc. minimum</td>
<td>Percentage of households living under or just around the social minimum, households of which at least one person makes money all year round, but below the social minimum as defined by the government</td>
<td>%</td>
<td>A, B</td>
</tr>
<tr>
<td>% welfare</td>
<td>Percentage of people receiving benefits from the government because they are unemployed or unable to work</td>
<td>%</td>
<td>A, B</td>
</tr>
<tr>
<td>% &gt; 65 years</td>
<td>Percentage of residents over 65 years of age</td>
<td>%</td>
<td>A, B</td>
</tr>
<tr>
<td>% &lt; 15 years</td>
<td>Percentage of residents under 15 years of age</td>
<td>%</td>
<td>A, B</td>
</tr>
<tr>
<td>% immigrants</td>
<td>Percentage of residents that were born outside of the Netherlands or whose parents were born outside of the Netherlands</td>
<td>%</td>
<td>A, B</td>
</tr>
<tr>
<td>D train station</td>
<td>Distance to the nearest train station</td>
<td>km</td>
<td>A, B</td>
</tr>
<tr>
<td>% &lt; 1945</td>
<td>Percentage of residencies built before 1945</td>
<td>%</td>
<td>B</td>
</tr>
<tr>
<td>% &gt; 1994</td>
<td>Percentage of residencies built after 1994</td>
<td>%</td>
<td>B</td>
</tr>
<tr>
<td>% apartments</td>
<td>Percentage of residences that house more than one family (i.e., apartment buildings)</td>
<td>%</td>
<td>B</td>
</tr>
<tr>
<td>Income</td>
<td>Mean yearly income per person (before tax)</td>
<td>( \text{[People x1000]} / \text{km2} )</td>
<td>B</td>
</tr>
<tr>
<td>Pop. density</td>
<td>Residents per km2</td>
<td></td>
<td>B</td>
</tr>
</tbody>
</table>
in a spatial weights matrix Anselin, 1988). The regression equation of a combined spatial lag and error model (SARMA) is composed of two parts which produce spatial lag (SAR) and spatial error models (SEM) individually. Eqs. (5)–(7) below show SAR, SEM, and SARMA models, respectively (Anselin & Bera, 1998):

\[
Y = \alpha + X\beta + \rho W Y + \epsilon
\]  
(5)

\[
Y = \alpha + X\beta + \lambda W u + \epsilon
\]  
(6)

\[
Y = \alpha + X\beta + \rho W Y + \lambda W u + \epsilon
\]  
(7)

where \(Y\) is a vector of observations of the dependent variable, \(\beta\) is the set of coefficients of the independent variables \(X\), \(W\) is the spatial weight matrix (i.e., contiguity matrix) involving the cost relations between observations (i.e., square grids), \(\rho\) and \(\lambda\) are the spatial autoregressive parameters, \(\epsilon\) is a normally distributed error term with zero mean and non-zero variance, and \(u\) is a vector of error terms assumed to have an autocorrelation. Moreover, the type of spatial weights matrix can influence the model results (Chi & Zhu, 2020), therefore two different contiguities (Queen and Rook) were specified to develop spatial weights matrices for all models used. Queen spatial weights include every neighbour that a cell shares an edge or a vertex, while Rook spatial weights matrix only includes those that share an edge (Fig. 4).

4.5. Scenario analysis

Two scenarios were created to evaluate the effects of future developments on the X-minute city scores. These developments are based on some existing plans regarding new bridge or tunnel connections for cyclists in the study area and changes in the speeds on the cycling network due to e-bike penetration in the bike market. In the first scenario, 9 bridge/tunnel connections were added to the network, based on the report for new cycling connections from Gemeente Utrecht (Gemeente Utrecht, 2019). These nine bridges and tunnels are shown in Fig. 5 and were added to the network.

For scenario 2, the speeds on the cycling network are changed to simulate the effect of an increasing number of e-bike riders. A distinction is made between urbanisation levels, and the type of infrastructure. In urbanisation levels 4 and 5 (less than 1000 addresses/km²), speed is 20 km/h for cycleways (separated infrastructure), and 18 km/h otherwise. In urbanisation levels 1, 2, and 3 (more than 1000 addresses/km²), speed is 18 km/h on cycleways and 17 km/h otherwise. All origins and destinations were kept the same and the X-minute metrics were calculated again.

5. Results

5.1. X-minute city scores and accessibility analysis

The accessibility per destination type is calculated for 10 min and 15 min threshold travel time and without any time threshold. The results of the accessibility analysis for 10 min threshold are presented in Fig. 6 as an example. The scores in Fig. 6 are standardized according to the lowest and highest values; thus, the results of the analysis are comparable. Afterwards, the accessibility scores were weighted according to the weighing approach (see Section 4.3), and the results are calculated for the 10 min threshold, 15 min threshold, and no travel time boundary (Fig. 7). The final scores are standardized according to the distribution of 10 min scores (both highest and lowest outliers); hence, the results are all on the same scale and comparable.

The most prominent difference between the CS10 and the CS15 is the presence of grid cells which has no score in the CS10. This is because these grid cells do not have accessibility to one or more of the destination types such as sports, healthcare, and entertainment. On the other hand, in CS15, there is only one grid cell at the northeast of the study area (Bilthoven) that has no score. Based on this definition, a mere 5.76% of the population in the study area does not have access to at least one of the destination types within 10 min, whereas, within 15 min, this number drops to a marginal 0.03%. Nonetheless, further research on identifying proper thresholds for citizens and marginal benefits of having more than one facility or service within a given threshold is needed to better assess the cities.

The overall CS10 show high values in the city centre of Utrecht and Bunnik (the eastern part of the study area). Also, in the surrounding towns, the centres score higher than the peripheries. The CS15 results are more homogenous, but still, the highest scores can be found in the city centre of Utrecht and Bunnik. Lower values are found in peripheries (IJSselstein and Houten, southwestern Utrecht).

Furthermore, Fig. 8 shows the absolute difference between the scores with different thresholds. The difference between the CS15 and the CS∞ is relatively small, as can be seen in Fig. 8-c. Only in Bunnik is the difference in score more considerable, with CS15 being substantially higher than CS∞. However, differences between CS15 and CS10, and between CS10 and CS∞, shown in Fig. 8-a and -b, are more substantial. People living in the peripheries of the city centre are especially disadvantaged due to a longer travel time, meaning they have to travel further to find the same number of opportunities as someone living in the city centre. CS10, on the other hand, is substantially higher than CS15 and CS∞ in the city centre. People living here benefit from the shorter travel time, but only if people in the other neighbourhoods also stay in their neighbourhood – can find their daily needs within 10 min 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 min city. Though it should be noted that the higher demand from the CS∞ 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 min boundary.

5.2. Bivariate clustering of scores and the socio-demographic variables

Fig. 9 presents bivariate local Moran’s I for the CS10 and key sociodemographic and neighbourhood characteristics hinting at the equity aspects. Results show that there is a low-high bivariate cluster of the CS10 and percentage of people with an immigration background, per-
percentage of people receiving welfare, and percentage of social housing in the neighbourhood Overvecht in Utrecht (centre-north). This indicates that the CS_{10} scores of these cells are low, while the number of people with an immigration background, the percentage of people receiving welfare, and the percentage of social housing are high. The people that live here are largely economically disadvantaged and have a greater risk of transport poverty (Kampert et al., 2019) and according to the CS_{10}, have less access to the services of the 10 min city. It should be noted that people with an immigration background generally cycle less than native Dutch people (Harms et al., 2014; Nello-Deakina & Harms, 2019) and an assessment based on the developed metric might overestimate the overall accessibility of areas with high immigrant populations due to lower share of cycling.

Kanaleneiland – a neighbourhood in the southwest of Utrecht, on the other hand, shows high-high bivariate clusters of the CS_{10} and the percentage of people with an immigration background, percentage of people receiving welfare, and percentage of social housing. This indicates that Kanaleneiland is a better practice neighbourhood where people with lower income and immigration backgrounds also have access to the services of the 10 min city.

Fig. 9-e shows a strong relationship between the percentage of children and the CS_{10} at Vleuten-De Meern and the south of Houten (western and southeastern part of the study area) where CS_{10} is low while the percentage of children is high. The CS_{10} is remarkably high in the city centre but relatively few children live here. Fig. 9-f shows the correlation between the CS_{10} and the percentage of elderly. Similar to the children, the CS_{10} is high in the city centre but relatively few ageing people live here. CS_{10} is relatively low in parts of Bilthoven (northeast Utrecht), Maarssen (northwest Utrecht) and the south of Nieuwegein (south Utrecht), while the percentage of elderly is high in these neighbourhoods. Some notable high-high clusters are located in Zeist and Bunnik (west Utrecht), where the elderly live in a 10 min city.

### 5.2.1. Spatial regression findings

Two spatial models (Table 5), Model A and Model B were developed (see Section 4.4). A spatial statistics test (Lagrange Multiplier - LM) was conducted to identify the best-fitting spatial autoregressive model, showing that only spatial dependence for lag was found to be significant both in Model A and Model B. Thus, a spatial lag model (SAR) was constructed for both models using a “Rook” contiguity for spatial weights matrix (based on Moran’s I value of the residuals). The dependent variables are the CS_{10} scores excluding job accessibility.

The results in model A indicate that the higher the percentage of households living under social minimum the higher the CS_{10} score,
which is a positive outcome for the equity and social fairness perspectives. Similarly, there is a significant positive relationship between the value of the CS10 and the percentage of people receiving welfare money. It is also an expected result that the larger the distance from the train stations, the lower the CS10 score, showing that train stations are generally the centre of urban activities and several services are close to the stations. An intriguing result is that there is a negative relationship between the CS10 score and the percentage of the population below 15 years old. The reason behind this outcome might be the preference of families with young children to live further away than urban centres, in suburban areas.

The Model B results are similar to Model A for the part of “transport poverty” indicators, except the percentage of households living under social minimum is not significant in Model B, whereas the percentage of people with an immigration background is significant. Results show that the percentage of people

---

**Table 5**

Spatial regression results, dependent variable: CS10 without job accessibility.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Model A</th>
<th></th>
<th></th>
<th></th>
<th>Model B</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \beta )</td>
<td>St. Error</td>
<td>Sig.</td>
<td>( \beta )</td>
<td>St. Error</td>
<td>Sig.</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.201</td>
<td>0.041</td>
<td>***</td>
<td>0.096</td>
<td>0.046</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>% soc. minimum</td>
<td>0.014</td>
<td>0.004</td>
<td>***</td>
<td>0.005</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% welfare</td>
<td>0.394</td>
<td>0.148</td>
<td>**</td>
<td>0.302</td>
<td>0.151</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>% &gt; 65 years</td>
<td>-0.034</td>
<td>0.097</td>
<td></td>
<td>0.045</td>
<td>0.099</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% &lt; 15 years</td>
<td>-0.520</td>
<td>0.121</td>
<td>***</td>
<td>-0.369</td>
<td>0.140</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>% immigrants</td>
<td>-0.112</td>
<td>0.073</td>
<td></td>
<td>-0.157</td>
<td>0.075</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>D train station</td>
<td>-0.043</td>
<td>0.010</td>
<td>***</td>
<td>-0.028</td>
<td>0.010</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>% &lt; 1945</td>
<td></td>
<td></td>
<td></td>
<td>0.010</td>
<td>0.003</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>% &gt; 1994</td>
<td></td>
<td></td>
<td></td>
<td>0.006</td>
<td>0.003</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>% apartments</td>
<td></td>
<td></td>
<td></td>
<td>0.075</td>
<td>0.036</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Income</td>
<td></td>
<td></td>
<td></td>
<td>0.005</td>
<td>0.073</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pop. density</td>
<td></td>
<td></td>
<td></td>
<td>0.083</td>
<td>0.025</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>Rho (lag)</td>
<td>1.446</td>
<td>1.467</td>
<td>***</td>
<td>1.384</td>
<td>1.658</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td><strong>Spatial dependency residuals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global Moran’s I z-value, p-value</td>
<td>1.323</td>
<td>0.186</td>
<td>***</td>
<td>1.201</td>
<td>0.230</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Model fit**

| LL                      | 113.90  | 135.69 |       |
| AIC                     | -211.79 | -245.38 |       |
| R2                      | 0.362   | 0.488  |       |

*** = \( P < 0.001 \)

** = \( P < 0.01 \)

* = \( P < 0.05 \)
with an immigration background living in a grid cell has a negative relationship with the CS_{10} score.

Furthermore, the percentages of houses constructed after 1994 (i.e., VINEX neighbourhoods (Schepers, 2021)) and before 1945 have positive relationships with the metric. Similarly, the higher the percentage of apartments (i.e., the type of housing in the grid cell) and the population density, the better the CS_{10} score. Income level, on the other hand, has no statistically significant effect on the metric.

5.3. Scenario analysis

Two different scenarios were tested to identify the effect of future investments (i.e., new bridges and tunnels) and potential changes in the cycling speeds due to e-bike penetration. Fig. 10 shows the difference between tested scenarios and the base scenario (i.e., current situation). These changes, although generally perceived as positive for mobility and accessibility, may result in negative effects for some regions due to competition effects which increase the demand for services while supply stays the same. For example, when Scenario 1 is implemented, CS_{10} increases in the city centre compared to the base scenario, while the score reduces (or does not change) around the city centre and for most of the towns in the periphery. 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. In Scenario 1, the CS_{10} increases for 45.8% of the population, and decreases for 45.2% of the population. For CS_{15}, it increases by 45.6% and decreases for 50.6% of the population. However, note that the change in scores is very small (between -0.02 and +0.02) in 80% of grids.

Scenario 2, in which cycling speeds are increased for cycling highways and outside of the city centres, is possible to observe a contrary effect compared to Scenario 1. Fig. 10 shows that towns in the periphery and areas surrounding the city centre benefit from the increasing cycling speeds the most, while Utrecht city centre experiences a reduction in CS_{10} scores. The situation in Scenario 1 and Scenario 2 is due to the change in the supply-demand relationship. When new connections or modes (e.g., e-bikes) are established to improve accessibility, more services become reachable by more people from further away areas; therefore, the demand is increasing while the supply for the local people remains the same. Because of this, the overall scores do not differ much between the base scenario and alternative scenarios (Scenario 1 and Scenario 2). Consequently, marginal improvement is observed in
the CS<sub>60</sub> scores, implying the ineffectiveness of detached infrastructure measures without taking the urban design and land use into account.

6. Discussion

6.1. Interpretation of results

The CS<sub>10</sub> and CS<sub>15</sub> in the study area show that while not every location is a 10 min city, almost every location is a 15 min city. However, this does not take the capacity of services into account, and some areas only minimally fulfill the requirements. Moreover, differences between the city centre of Utrecht and the surrounding periphery and towns are large, indicating an equity issue. It is also worth noting that an analysis focused on walking may reveal that Utrecht itself is also not a 10 min (walking) city. The results also show that people on welfare and people with low income generally do not have lower accessibility to services in the 15 min city in the study area, in contrast to the transport poverty literature (Jorritsma et al., 2018; Kampert et al., 2019). This finding reinforces the notion that cycling can be an effective solution to maintain transport equity in which the same opportunities are accessible to everyone.

From a social fairness perspective, people with immigration backgrounds (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<sub>10</sub> is lower. This may indicate a disadvantage for people with an immigration background. Moreover, people with immigration backgrounds generally have a lower cycling rate than other groups in the Netherlands (CBS, 2021). Therefore, the X-minute city score based on cycling might be even lower than the calculated levels when the preference for cycling as a mode is taken into account.

People with children (under 15 years) also tend to live in neighbourhoods where the CS<sub>10</sub> is lower. Children are highly dependent on the bikeability and walkability of their place of residence to achieve independence at an early age, and they might benefit from having services such as schools, sports clubs, and recreation more accessible.

6.2. Practical implications

Improvements to the 10- or 15 min city scores can be achieved by economic and policy stimulation of more small stores, restaurants, and other leisure activities in neighbourhoods that 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 in such schemes amongst the political parties. The CS<sub>60</sub> 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 proposed methodology is also effective to assess the impacts of new implementations such as network improvements or new housing developments on accessibility. For example, a scenario with improved cycling connections (i.e., bridges, tunnels, etc.) showed no significant changes in the score, aside from a small increase in the city centre. The metric can be used to evaluate scenarios like this and select the 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<sub>N</sub> they provide.

6.3. Limitations and future research

It should be noted that the accessibility analysis in this study does not consider the quality and safety of the cycling network, which 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 the 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. A possible future research direction can be including the capacity of services, diversity measures for restaurants and shops, and the quality of the network.

Another possible venue for future research would be to include level of traffic stress (LTS) classification by making a distinction between a low-stress cycling network and a complete cycling network to take the quality of cycling infrastructure into account. In this way, the X-minute metric can be even further deployed to assess results for different population groups such as children and elderly preferring low-stress bike routes, and it would provide insights into the safety of cyclists in the X-minute city. Furthermore, expanding the metric with walking accessibility scores may lead to more nuanced conclusions about a city, since some people that are unable to bike or use a similar mode of transport can walk. For walking, however, due to lower speed using 100-by-100 m grid cells or building-level analysis will be much more accurate than the 500-by-500 m grid cells used in this study. This significantly increases the data need and computational efforts for large network analysis.

In this study, a weighing scheme derived from the DMP recorded travel data was used, which only captures what people can do and currently do, but not what they want to do (preference). In the 15 min city, all six service categories as defined by Moreno are important to be present within the threshold. Personal preferences can be identified through surveys (Weng et al., 2019) and used as the weights of different services in the metric.

7. Conclusion

The main objective of this study was to develop a cycling accessibility metric for X-minute cities and apply this in a case study. An aggregated metric of gravity-based 2SFA 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 an X-minute city and reveal problematic areas that may be prioritised to improve the score.

The number and type of services in the 15 min city are not universally agreed upon, with different studies using different definitions and destination types. In this study, nine destination types were defined. 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 dimensions in the accessibility scores. The same is true for destination types of food and commercial (originally commerce). The 15 min city is different for every individual, 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, the definition of the 15 min city can be modified to fit the culture of the location under study and its inhabitants. It is worth mentioning that a few destination types identified in the literature, namely hospitals, pharmacies, banks, religious facilities, and post offices, are not included in the developed metric. That is because these services are not very influential in the context of the study area. Nonetheless, there is still room for future research to identify the set of destination types for different contexts and user preferences. Therefore, the developed methodology allows for modification of the weights of the destination types, as well as the distance decay functions.

The results of the metrics show that the study area is a 15 min city for almost 100% of the population within the area, and a 10 min city for 94% of the population in the study area, with at least one service of each destination type accessible within 10 min 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 min city. This is not surprising, as the city of Utrecht is well-known as a cycling city due to its cycling-friendly infrastructure. Furthermore, low-income groups do not have lower cycling accessibility to the services of the 15 min city in the study area, reinforcing the notion that the 15 min cycling city may reduce transport inequalities caused by not having access to a private car. However, some areas outside of the city centre and the town cores barely meet the definition of one service per destination type accessible within 10 or 15 min.

Scenario analyses show that improvement of the X-minute cycling city is not as straightforward with a net positive increase as a result of new connections or changes in travel speeds. While some areas benefit from new changes, in others the X-minute city metric decreases as a result of increased demand simultaneously with increased accessibility using the new connections. 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 X-minute cities.

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

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Goudappel for providing support for this research. The opinions, results, and findings expressed in this manuscript are those of the authors and do not necessarily represent the views of the aforementioned persons and institutions.

Appendix

Fig. A, Table A

<table>
<thead>
<tr>
<th>Destination</th>
<th>All</th>
<th>Jobs</th>
<th>Commercial</th>
<th>Food</th>
<th>Education</th>
<th>Sports</th>
<th>Healthcare</th>
<th>Restaurants, bars</th>
<th>Entertainment</th>
<th>Recreation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trip duration (min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>12.1</td>
<td>15.7</td>
<td>10.3</td>
<td>8.8</td>
<td>10.1</td>
<td>10.9</td>
<td>11.8</td>
<td>15.9</td>
<td>13.7</td>
<td>19.6</td>
</tr>
<tr>
<td>Std</td>
<td>10.4</td>
<td>11.5</td>
<td>8.9</td>
<td>7.9</td>
<td>7.9</td>
<td>8.3</td>
<td>8.4</td>
<td>16.4</td>
<td>11.6</td>
<td>22.4</td>
</tr>
<tr>
<td>Min</td>
<td>0.7</td>
<td>1.2</td>
<td>1.2</td>
<td>0.9</td>
<td>0.8</td>
<td>1.0</td>
<td>0.7</td>
<td>1.4</td>
<td>1.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Max</td>
<td>215.8</td>
<td>215.8</td>
<td>173.1</td>
<td>197.1</td>
<td>136.5</td>
<td>146.8</td>
<td>95.2</td>
<td>193.6</td>
<td>116.5</td>
<td>196.2</td>
</tr>
</tbody>
</table>


