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DOI

[10.1016/j.jtrangeo.2024.103861](https://doi.org/10.1016/j.jtrangeo.2024.103861)

Publication date

2024

Document Version

Final published version

Published in

Journal of Transport Geography

Citation (APA)

Spienburg, L., van Lint, H., & van Oort, N. (2024). Synergizing cycling and transit: Strategic placement of cycling infrastructure to enhance job accessibility. *Journal of Transport Geography*, 116, Article 103861. <https://doi.org/10.1016/j.jtrangeo.2024.103861>

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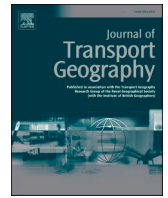
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Synergizing cycling and transit: Strategic placement of cycling infrastructure to enhance job accessibility

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ARTICLE INFO

Keywords:

Accessibility
Multimodality
Utility-based indicator
Bike-and-ride
Cycle lanes

ABSTRACT

Enabling cycling at the home side or at the activity side of transit trips has been recognized as a promising solution to address transit network discrepancies and enhance connectivity between residents and employment opportunities. However, this multimodal solution is conditional to bicycle parking and cycle lanes, and urban planners need tools to identify relevant locations for these infrastructures. This research presents a novel method to quantify the impact of potential cycling infrastructures on job accessibility. Using a logsum-based indicator, we assess the spatial distribution of accessibility improvements across neighborhoods when residents have the option to cycle from and to transit stops. Then, we quantify the individual contribution of every potential bicycle parking location and cycle lane to the overall accessibility improvements. The proposed approach offers valuable support to urban planners in identifying the best locations for (1) multimodal bicycle parking and (2) cycle lanes to foster synergies between cycling and transit. To demonstrate the efficacy of our method, we apply it to the case study of Amsterdam. The findings reveal that bicycle parking at metro stops and cycle lanes connecting these stops to dense and remote locations contribute the most to accessibility improvements, as they effectively connect these areas to high-frequency and high-speed transit lines. Additionally, we observe that few strategic infrastructures account for most of the accessibility improvements in Amsterdam.

1. Introduction

Accessibility, defined here as the ease for inhabitants to reach opportunities, stands out as one of the key indicators for livability in a city (Hansen, 1959; Dalvi and Martin, 1976). Accessibility's scope extends to a variety of key urban opportunities, including amenities, green spaces, healthcare, education, and jobs, all of which contribute to the overall quality of life for urban residents (Lotfi and Koohsari, 2009; Slovic et al., 2019; Miliás and Psyllidis, 2022; Teeuwen et al., 2023). Amidst these different dimensions of accessibility, job accessibility is of particular importance, as it has a substantial positive effect on labor market outcomes, notably on employment and income (Jin and Paulsen, 2018; Bastiaanssen et al., 2021). Consequently, improving job accessibility is generally a key motive for public authorities to develop transport infrastructure.

Concurrently, cities are adopting green agendas to reduce greenhouse gases emissions, responding to calls for sustainability, both from concerned citizens and international organizations (United Nations, 2017; Municipality of Paris, 2020; Municipality of Amsterdam, 2020).

Mobility is a significant contributor to greenhouse gases emissions and this context gives rise to a twofold challenge for cities. They must develop transportation infrastructure that not only improves accessibility but also aligns with sustainability goals. In this endeavor, transit and cycling infrastructures are taking center stage, as these two modes associate with lower emissions (Maizlish et al., 2017; Saltykova et al., 2022; Ballo et al., 2023).

The integration of cycling with public transport, a form of multimodality, has emerged as a promising approach to improve accessibility while complying with sustainability engagement (Tønnesen et al., 2021). This combination not only reduces transit access and egress times but also provides residents with direct access to high-frequency transit lines, reducing the need for transfers (Kager et al., 2016). This integration involves the implementation of continuous cycle lanes serving transit stops coupled with bicycle parking facilities (Jonkeren et al., 2019). Such infrastructures come with associated costs necessitating a quantitative assessment of the resulting gains in accessibility. To this end, several studies in the literature address this need by predicting the overall accessibility improvements when cycling can be combined with

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<https://doi.org/10.1016/j.jtrangeo.2024.103861>

Received 1 June 2023; Received in revised form 8 February 2024; Accepted 29 March 2024

Available online 8 April 2024

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transit (Geurs et al., 2016; de Souza et al., 2017; Pritchard et al., 2019a, 2019b; Zuo et al., 2020). For instance, Pritchard et al. (2019b) and Zuo et al. (2020) measure the additional number of jobs reachable within a time budget when commuters can cycle from and to transit stops, and assess how those improvements are distributed across income groups in the cities of São Paulo and Hamilton County respectively.

However, the approaches proposed in these studies lack the ability to offer precise guidance on where to develop these lanes and establish bicycle parking facilities. They effectively quantify the accessibility improvements when cycling can be combined with transit, but they do not inform on where to implement infrastructures in order to harness these improvements. Moreover, most of these studies employ what Geurs and van Wee (2004) coin as location-based indicators, measuring the change in the number of accessible jobs per location. These location-based indicators do not effectively capture trade-offs commuters typically weigh in when presented with various travel alternatives. In practice, such trade-offs are often encountered when cycling can be combined with transit. As an example, commuters might select a route that involves a lengthier overall journey by cycling from their residences to a high-speed transit line, in order to bypass a transfer. Neglecting these trade-offs that commuters weigh in when developing transport infrastructure can result in a mismatch between investment and the inhabitants' need. For instance, a bicycle parking that allows to combine cycling with transit may reduce travel time, but the potential benefits might go unrealized if commuters prefer to cycle directly to their destinations rather than combine modes. Logsum-based measures account for these trade-offs, as they weigh relevant travel attributes (e.g. walking time or number of transfers) based on choice modeling theory (Ben-Akiva and Lerman, 1985). These logsum indicators usually rely on experiments where travelers express their preferences to determine how individuals compromise between travel attributes. In the literature, they have been successfully applied to assess accessibility by public transport (Nassir et al., 2016; Jang and Lee, 2020). Yet, no studies have leveraged their ability to capture trade-offs between cycling and transit modes to assess the relevance of cycle-and-ride infrastructures. To the best of the author's knowledge, no method identifies the best locations for cycle lanes and bicycle parking in order to exploit the synergies between cycling and transit, while considering the trade-offs commuters do between cycling, transit, and combining both. In this paper, we address this knowledge gap. We propose a method to quantify the increase in job accessibility when cycling is enabled at the home or the job side of trips, and to measure the marginal contribution of any potential cycle lane and bicycle parking to this increase.

In this study, we measure accessibility with a logsum-based indicator, where all travel time components (walking time, waiting time, in-vehicle time, burden of transferring, burden of using a bicycle) are weighted based on the traveler's perception. In our accessibility assessment, we compare a benchmark scenario where travelers can walk, cycle, and use public transport to a counterfactual scenario where travelers can either cycle at the home side or at the job side of the trip. We can then assess the spatial distribution of the gains in job accessibility in a city, and quantify the individual contribution of every cycle lane and bicycle parking to the overall accessibility improvement.

We use the municipality of Amsterdam as a case study to showcase our method. In this city, the cycling infrastructure is highly developed (Aston et al., 2021). Most of the streets exhibit excellent cyclability, and cycle-and-ride parking locations are implemented in most train stations. However, only a few metro stops host such facilities, while it could increase significantly job accessibility. Our method successfully quantifies the gains in accessibility for each transit stop. Our method is easily reproducible to any city if the following data are available: the spatial distribution of inhabitants and jobs, transport schedule, and data on the street network.

The paper is structured as follows: Section 2 presents the method used to compute accessibility and the impact of bike-and-ride locations on accessibility, Section 3 introduces the data sets used for the analysis,

Section 4 shows the result for the case study of Amsterdam, and Section 5 discusses potential improvements and further research based on this work.

2. Methodology

We measure accessibility using a logsum indicator, where we weigh job opportunities and travel alternatives using a utility-based travel impedance (Subsection 2.1). The further the job opportunity, the less attractive, and the different travel components (e.g. walking time, number of transfers) are weighted based on the traveler's perception (Subsection 2.2). We compare a benchmark scenario, where travelers can walk, cycle, and take public transport to commute with a multimodal scenario, where travelers can also combine cycling and transit. We then retrieve the individual contribution of each cycling infrastructure (bicycle parking and cycle lanes) in the overall accessibility improvements (Subsection 2.3). For each origin-destination couple, we determine the walking and cycling time from home and job locations to transit stops using Dijkstra's algorithm on the street network and compute transit time by exploring the transit schedule dataset for transit legs (Subsection 2.4).

2.1. Measuring accessibility

2.1.1. Accessibility indicator

We define a logsum-based indicator to measure accessibility using the formulation of Ben-Akiva and Lerman (1985), see Eq. (1). An inhabitant living in spatial unit k can travel to spatial unit i to reach J_i jobs using one of the four following travel alternatives, each associated with a certain utility: walking (U_{kiw}), cycling (U_{kic}), public transport (U_{kip}), or combining transit with cycling (U_{kim} , m standing for multimodal). In the latter alternative, inhabitants cycle either at the home side or at the job side of their transit trip, but not at both home and job sides. λ is the scale parameter of the logsum indicator, we estimate it in Subsection 2.2.3.

$$a(k) = \frac{1}{\lambda} \log \left[\sum_i J_i (e^{\lambda U_{kiw}} + e^{\lambda U_{kic}} + e^{\lambda U_{kip}} + e^{\lambda U_{kim}}) \right] \quad (1)$$

The cumulative accessibility in the city is the sum of the accessibility in all spatial units k weighted by their population N_k .

$$A = \sum_k N_k \cdot a(k) \quad (2)$$

2.1.2. Accessibility improvements

To measure the accessibility improvements resulting from enabling multimodality, we compare the multimodal scenario to a benchmark scenario where travelers cannot combine transit with cycling (U_{kim} is set to $-\infty$). Eq. (3) represents the increase in accessibility $\Delta A(k)$ in spatial unit k . Eqs. (4) to (6) express the total gain in accessibility in the city.

$$\Delta A(k) = [a_m(k) - a_b(k)] \quad (3)$$

$$\Delta A = \sum_k N_k \cdot [a_m(k) - a_b(k)] \quad (4)$$

$$= \frac{1}{\lambda} \sum_k N_k \cdot \log \left[\frac{\sum_i J_i (e^{\lambda U_{kiw}} + e^{\lambda U_{kic}} + e^{\lambda U_{kip}} + e^{\lambda U_{kim}})}{\sum_i J_i (e^{\lambda U_{kiw}} + e^{\lambda U_{kic}} + e^{\lambda U_{kip}})} \right] \quad (5)$$

$$= \frac{1}{\lambda} \sum_k N_k \cdot \log \left[1 + \frac{\sum_i J_i e^{\lambda U_{kim}}}{\sum_i J_i (e^{\lambda U_{kiw}} + e^{\lambda U_{kic}} + e^{\lambda U_{kip}})} \right] \quad (6)$$

2.2. Utility function

2.2.1. General definition

We use a utility function U_{kj} depending on the utility V_j of being able

to reach job j minus the travel disutility T_{kj} of a travel alternative between someone's home location k and job j . In this work, we assume that V_j is the same for every inhabitant and constant across all jobs. We note it V_{op} .

$$U_{kj} = V_j - T_{kj} = V_{op} - T_{kj} \quad (7)$$

The increase in accessibility ΔA measured in Eq. (6) does not depend on V_{op} , under the assumption that V_{op} is constant. In this formula, the factors $e^{\lambda V_{op}}$ in the nominator and the denominator inside the log function cancel out (see Eqs. (8) and (9)).

$$\frac{\sum_i J_i e^{\lambda U_{kim}}}{\sum_i J_i (e^{\lambda U_{kiw}} + e^{\lambda U_{kic}} + e^{\lambda U_{kip}})} = \frac{\sum_i J_i e^{\lambda V_{op}} e^{-\lambda T_{kim}}}{\sum_i J_i e^{\lambda V_{op}} (e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}})} \quad (8)$$

$$= \frac{e^{\lambda V_{op}} \sum_i J_i e^{-\lambda T_{kim}}}{e^{\lambda V_{op}} \sum_i J_i (e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}})} \quad (9)$$

2.2.2. Generalized travel time

In this work, we aim to account for travelers' perceived disutility of the different trip components (walking time, waiting time...) using a generalized travel time. Each component is weighted depending on the traveler's perception of it. For instance, waiting time may be perceived as twice as bad as in-vehicle time for travelers.

The weights in the generalized travel time are determined from the literature on perceived travel time in the Netherlands, based on the work from van Mil et al. (2021) and from Ton et al. (2020). These two articles assess the behavior of travelers combining transit and cycling. Ton et al. (2020) focus on the tram-bicycle combination in the Hague, while van Mil et al. (2021) focus on the train-bicycle combination in Amsterdam. Table 1 provides the reader with the weights for each trip component in the generalized travel time shown in Eq. (10).

$$T_{kix} = \begin{cases} \beta_{walk} t_{walk} & \text{if } x = w \\ \beta_{bike} t_{bike} + \beta_{bike\ use} \delta_{bike\ use} & \text{if } x = c \\ \beta_{veh} t_{veh} + \beta_{wait} t_{wait} + \beta_{walk} t_{walk} + \beta_{transfer} n_{transfer} & \text{if } x = p \\ \beta_{veh} t_{veh} + \beta_{wait} t_{wait} + \beta_{walk} t_{walk} + \beta_{bike} t_{bike} + \beta_{bike\ use} \delta_{bike\ use} + \beta_{transfer} n_{transfer} & \text{if } x = m \end{cases} \quad (10)$$

2.2.3. Definition of the scale parameter

The accessibility indicator presented in Eq. (1) depends on the unknown scale parameter λ . We define this parameter from the median generalized commute time in the city.

The probability for someone to pick a job in location i given a certain generalized travel time is shown in Eq. (11), where J_i is the number of jobs in i , and λ is the scale parameter to estimate. By definition, the probability for a random person to work in a job where the generalized travel time is larger than the population's median generalized commute time is 0.5 (see Eq. (12)). We use this equality to estimate λ , given a certain T_{med} .

$$P(I = i) = \frac{J_i (e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}})}{\sum_i J_i (e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}})} \quad (11)$$

Table 1

Values of the different weighting parameters in the generalized travel time. The unit of time is seconds.

| | In-vehicle time | Walking time | Waiting time | Transfer [s] | Cycling time | Bike use [s] |
|--------|-----------------|--------------|--------------|--------------|--------------|--------------|
| Weight | 1 | 2.72 | 2.88 | 454 | 4.45 | 534 |

$$P(t_{ki} \geq T_{med}) = \frac{\sum_{i: T_{ki} \geq T_{med}} J_i (e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}})}{\sum_i J_i (e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}})} = \frac{1}{2} \quad (12)$$

Eq. (12) can be rewritten as Eq. (13). Eq. (13) cannot be solved analytically, because it has no closed form. It cannot be easily solved numerically either, because of the number of exponential terms on both sides of the equation.

$$\sum_{i: T_{ki} \geq T_{med}} (J_i e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}}) = 0.5 \cdot \sum_i J_i (e^{-\lambda T_{kiw}} + e^{-\lambda T_{kic}} + e^{-\lambda T_{kip}}) \quad (13)$$

To reduce the number of exponential terms, we simplify Eq. (13). First, we express the terms as a function of time t , rather than as a function of the origin and the destination (see Eq. (14)), and assume that there is only one travel alternative available between the origin and the destination. The number of jobs J_i at destination i becomes the number of jobs $J(t)$ requiring travel time t to reach them. Second, we express Eq. (14) as an integral over time rather than a sum (Eq. (15)), and change the bounds of the integral, to drop the 0.5 coefficient on the right-hand side (Eq. (16)). Third, we assume that $n(t)dt$ can be expressed as $\alpha \cdot t \cdot dt$, where α is constant. This assumption reflects that the area reachable between t and $t + dt$ is proportional to t . For instance, if the surface reachable within travel time t is a disk given a speed of v , the surface reachable between t and $t + dt$ is a ring of area $2\pi v^2 t dt$, see Fig. 1. In this example, α is $2\pi v^2$.

$$\sum_{t \geq T_{med}} n(t) \cdot e^{-\lambda t} = 0.5 \cdot \sum_i n(t') \cdot e^{-\lambda t'} \quad (14)$$

$$\int_{T_{med}}^{\infty} n(t) \cdot e^{-\lambda t} dt = 0.5 \cdot \int_0^{\infty} n(t') \cdot e^{-\lambda t'} dt' \quad (15)$$

$$\int_{T_{med}}^{\infty} n(t) \cdot e^{-\lambda t} dt = \int_0^{T_{med}} n(t') \cdot e^{-\lambda t'} dt' \quad (16)$$

$$\int_{T_{med}}^{\infty} t \cdot e^{-\lambda t} dt = \int_0^{T_{med}} t' \cdot e^{-\lambda t'} dt' \quad (17)$$

Finally, we integrate both sides of Eq. (17) and obtain Eq. (18), which we can solve numerically for a given T_{med} . For a median

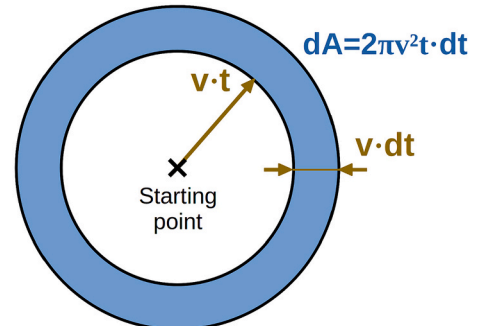


Fig. 1. Area reachable between travel times t and $t + dt$ from a starting point.

generalized travel time T_{med} of 45 min, λ equals $6.2 \cdot 10^{-4} \text{ s}^{-1}$.

$$e^{-\lambda T_{med}} (\lambda T_{med} + 1) = 0.5 \quad (18)$$

2.3. Contribution of a cycling infrastructure in the total accessibility improvements

2.3.1. Definition of cycling infrastructure

In this work, we assume that multimodal trips are conditional upon (1) a cycle lane between the origin and the destination of the cycling leg and (2) a bicycle parking at the transit stop (also called cycle-and-ride facility in this work). Some of the transit stops may be close to each other. We construct a set of possible cycle-and-ride facilities, assuming that stops that are less than 100 m away from a cycle-and-ride facility are served by it.

2.3.2. Measuring the contribution of cycling infrastructure

In this study, we establish a clear distinction between two components of cycling infrastructure being cycle lanes and bicycle parking. Together, they play a pivotal role in enabling multimodal travel alternatives.

2.3.2.1. Cycle lanes. These infrastructures are comprised of road segments providing a pathway for cyclists. Their layout can vary based on the specific case study. Examples of cycle lane layouts may include painted lanes, dedicated cycling paths, or other design variations. It is essential to note that in the context of this research, we consider a cycling leg as feasible only when a fully continuous cycle lane is available from an individual's home to the selected transit stop.

2.3.2.2. Bicycle parking. Such infrastructures allow commuters to drop their bicycle at a specific location. In the context of this work, we investigate those located at transit stops, also called cycle-and-ride parking. For a cycling leg to be considered as a feasible option, the presence of bicycle parking at the transit stop is a prerequisite, otherwise utility U_{kim} in Eq. (1) is set to $-\infty$. We assume that individuals have the option to park their bicycles at their residence and work place.

When measuring the overall accessibility improvements (Eq. (6)), we can isolate the individual contribution of each particular cycling infrastructure (either cycle-and-ride parking or a cycle lane). We measure the individual contribution $\Delta A(s)$ of a particular cycling infrastructure s , by accounting only for the travel alternatives enabled by infrastructure s (see Eq. (19)). The binary variable $\delta_{ki}(s)$ indicates whether the cycling leg of the multimodal travel alternative τ_{kim} between origin k and destination i passes by cycling infrastructure s .

$$\Delta A(s) = \frac{1}{\lambda} \sum_k N_k \cdot \log \left[1 + \frac{\sum_i \delta_{ki}(s) \cdot J_i \cdot e^{\lambda U_{kim}}}{\sum_i J_i (e^{\lambda U_{kiw}} + e^{\lambda U_{kic}} + e^{\lambda U_{kip}})} \right], \quad \delta_{ki}(s) = \begin{cases} 1 & \text{if } s \in \tau_{kim} \\ 0 & \text{otherwise.} \end{cases} \quad (19)$$

2.4. Measuring the generalized travel time for each alternative

2.4.1. Walking and cycling alternatives

We compute the generalized travel time for walking and cycling alternatives between homes and job locations using the street layout. Each street segment is associated with a walking speed and a cycling speed, and we use Dijkstra's algorithm to find the fastest walking and cycling paths between origins and destinations. We set the walking speed to 4.5 km/h for all segments. We extract the average cycling speed per street segment from an external dataset (see Subsection 3.3 for more details on the dataset). We stop exploring the street network when the travel time exceeds 20 min to limit the computational complexity.

2.4.2. Transit and multimodal alternatives

The transit and multimodal alternatives are divided into three legs:

the home-side leg, the job-side leg, and the transit leg. As in Subsection 2.4.1, we compute the walking and cycling times for the home-side and job-side parts of the trip using Dijkstra's algorithm. Here, we stop exploring the street network when the home-side (or job-side) leg time exceeds 15 min. Hence, the walking (respectively cycling) catchment area of a transit stop is composed by all street nodes reachable within 15 min of walking (respectively cycling). Then, we compute the transit times from stops to stops from the transit schedule, storing separately the in-vehicle time, the waiting time, and the number of transfers. The waiting time is averaged over the morning time period.

3. Case study and data used

We use the municipality of Amsterdam to demonstrate our approach in a real case study. We measure the increase in accessibility to jobs when cycling can be combined with transit, for all spatial units belonging to the municipality of Amsterdam in our dataset. The main transit operator in Amsterdam is GVB, which also serves suburban neighborhoods in Amstelveen and Diemen. Therefore, we include the jobs located in the vicinity of a GVB stop outside of Amsterdam (less than 3 km as the crow flies) in our analysis, in addition to jobs inside the municipality of Amsterdam. The transit service coverage on foot (respectively by bicycle) by all street nodes reachable within 15 min of walking (respectively cycling).

Subsections 3.1 to 3.3 describe the different datasets used in the analysis. Fig. 2 represents the perimeter of study with the municipality of Amsterdam and the additional job locations considered in the suburbs of Amsterdam. We also represent the transit network and the street layout on this map.

3.1. Socio-demographic data

We choose the year 2019 in our case study to consider the GVB network after the commissioning of the North-South-line (Noord-Zuidlijn, or metro 52), connecting the city north of the IJ-water with the historic center and the rest of Amsterdam. This connection results in a substantial change in the GVB network (Brands et al., 2020). We retrieve the spatial distribution of jobs and inhabitants from demographic data from the municipality of Amsterdam designed for transport modeling (Municipality of Amsterdam, 2016). In this dataset, the region of Amsterdam (overarching Amsterdam and neighboring municipalities) is disaggregated into spatial units providing the number of jobs and inhabitants for the years 2015 and 2020. These spatial units, defined by the municipality of Amsterdam, correspond to a spatial disaggregation of the Dutch *buurten*, an administrative definition of neighborhoods, see Municipality of Amsterdam (2016) for more details. The median area for the spatial units in our dataset is 0.1 km^2 (corresponding to a $300 \times 300 \text{ m}^2$ spatial unit). The year 2015 is based on census data, while the year 2020 is projected (projections established before Covid). Data for 2019 are estimated by doing a linear interpolation from the years 2015 and 2020.

3.2. General transit feed specification data (GTFS)

We retrieve transit schedules from General Transit Feed Specification data in the Netherlands (Open, 2019). The date chosen for the analysis is Thursday, September 24th, 2019. This date is after the commissioning of the Noord-Zuidlijn, and before the COVID-19 crisis that affected public transport schedules. We focus on the morning on-peak hour, from 7:30 to 10:00. We consider all transit modes operated by the GVB operator: metro, tram, bus, and ferry. In Fig. 2, we do not show the buses and ferry lines on the maps in the figures of this paper for clarity purposes, yet they are included in the analysis.

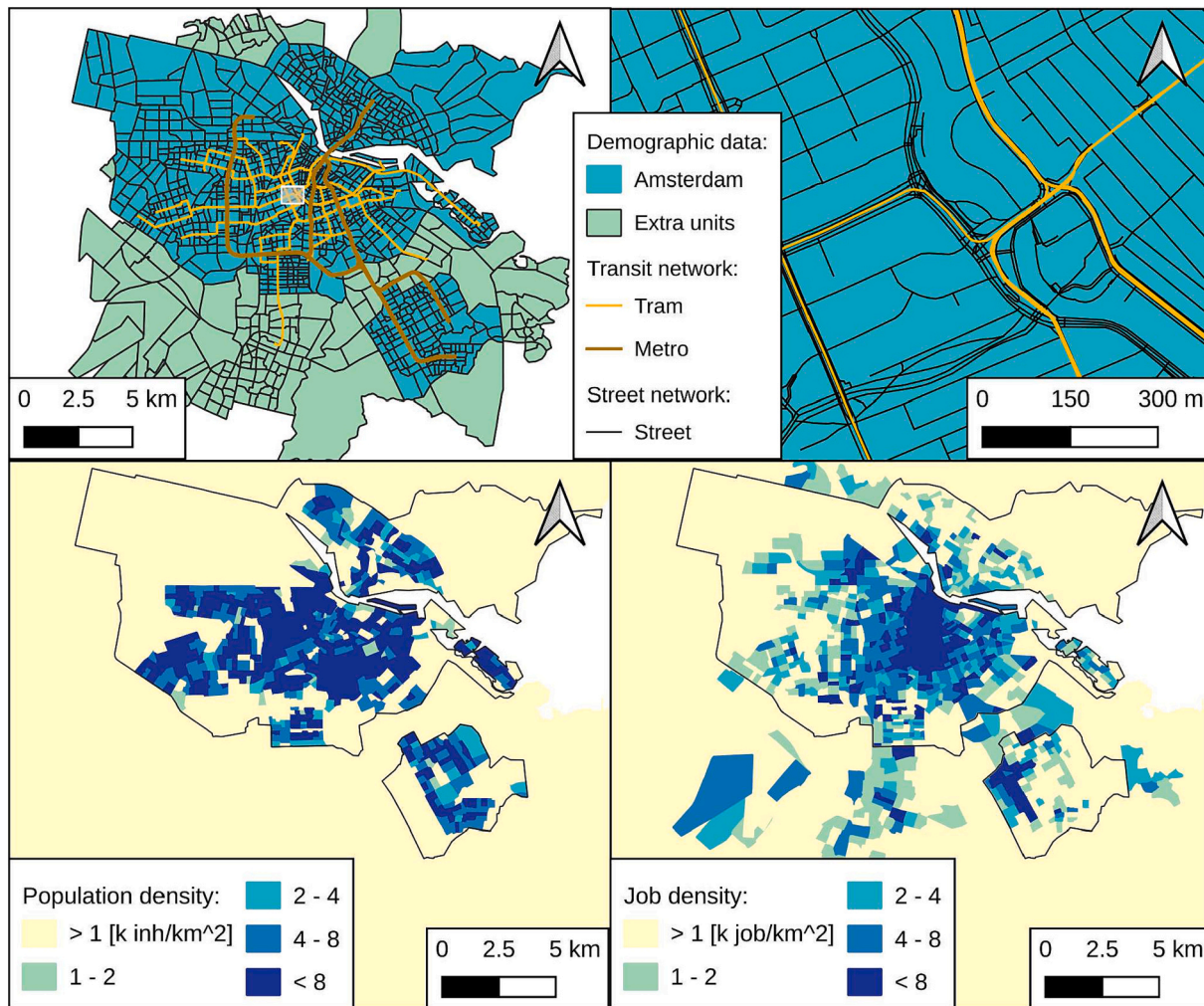


Fig. 2. Spatial representation of the datasets used in this work, bus lines and ferries are not displayed but considered in the analysis. Only the inhabitants in Amsterdam are considered in this work. All jobs within a 3 km buffer of transit jobs are considered in this work.

3.3. Street data

We use street network data to estimate walking and cycling times. We retrieve the street layout from the [OpenStreetMap \(2020\)](#) database using the Osmnx library in Python ([Boeing, 2017](#)). We use the [Fiets Telweek \(2017\)](#) dataset to extract cycling speed per street segment in Amsterdam. This dataset provides the average cycling speeds per street segment in the Netherlands based on GPS data and covers 50% of the total road length in OpenStreetMap for our case study. For the missing links, we set the cycling speed to 15 km/h for non-pedestrian links and 4.5 km/h for pedestrian links.

4. Results

We apply the method for the municipality of Amsterdam to measure accessibility to jobs in the benchmark scenario (travelers can walk, cycle, or use public transport to commute), as well as the accessibility improvements due to enabling multimodality ([Subsection 4.1](#)). Then, we investigate the contribution of each cycle lane and each cycle-and-ride infrastructure to the total accessibility improvements ([Subsection 4.2](#)).

4.1. Accessibility improvements

After measuring the accessibility in the benchmark and the multimodal scenarios for each spatial unit, we can assess how accessibility and accessibility improvements are distributed in space and across the population. We show these results in [Fig. 3](#), where we scale the logsum indicator according to its average and standard deviation. In the benchmark scenario, accessibility is high in the city center, average in the outskirts around metro and tram lines, and low in the outskirts further away from transit lines. In the city center, travelers are within walking distance of many lines, resulting in low walking time at the home side of the trip and few transfers. In the outskirts in the vicinity of metro and tram lines, travelers are within walking distance of high-frequency transit lines but may have to transfer to reach certain parts of the city. Lastly, travelers living in the outskirts away from metro and tram lines combine longer walking time at the home side of the trip and more transfers, reducing the ease to reach job opportunities. The distribution of accessibility across the population is left-skewed (bottom left of [Fig. 3](#)), indicating that many inhabitants have an accessibility that is slightly larger than the city average, while few inhabitants have an accessibility that is significantly lower than the city average.

Bottom left: distribution of accessibility levels across the population.

Top right: spatial distribution of the increase in accessibility when multimodality is enabled.

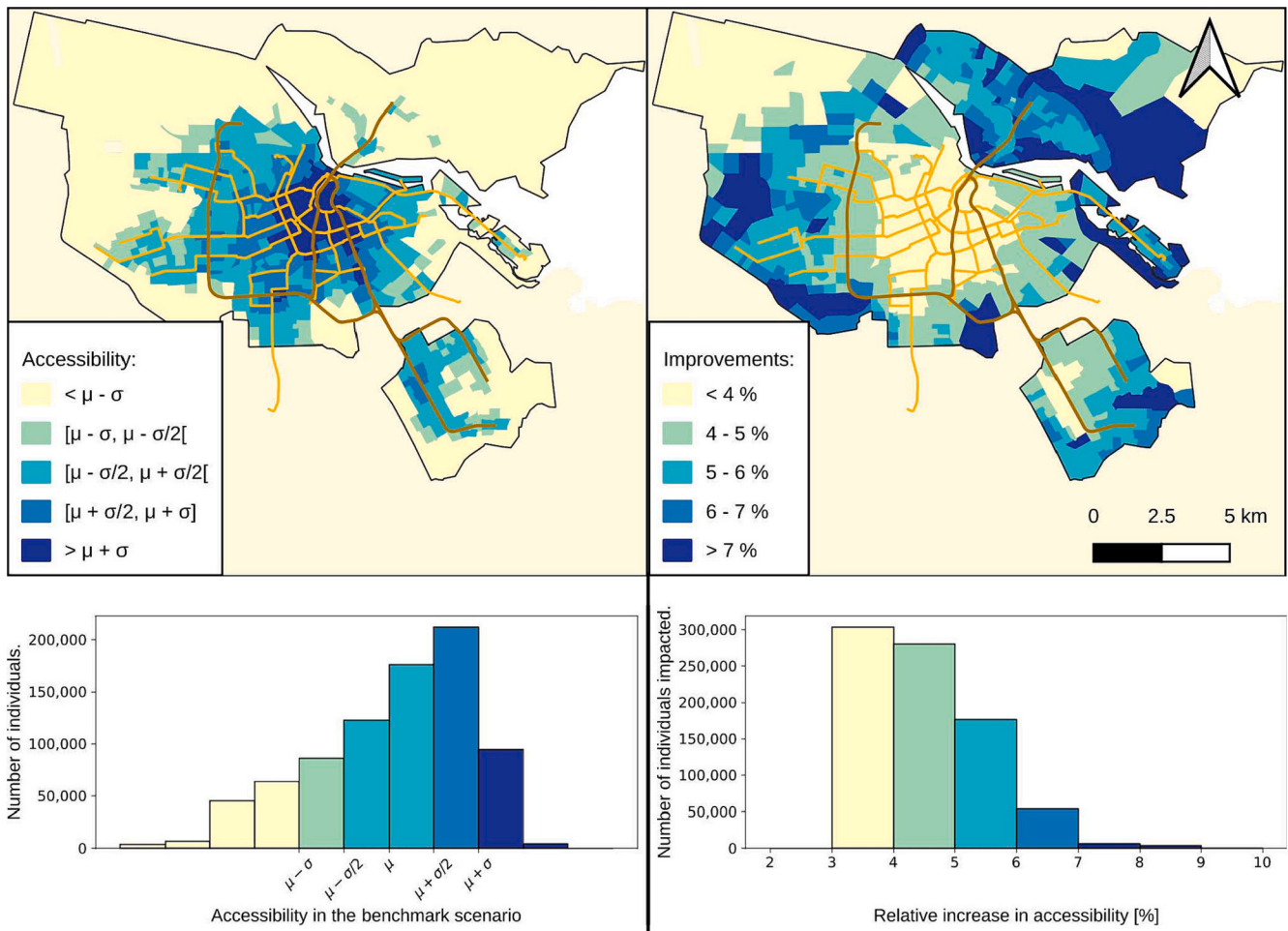


Fig. 3. Top left: spatial distribution of accessibility levels in the benchmark scenario, in comparison to the city average μ and standard deviation σ .

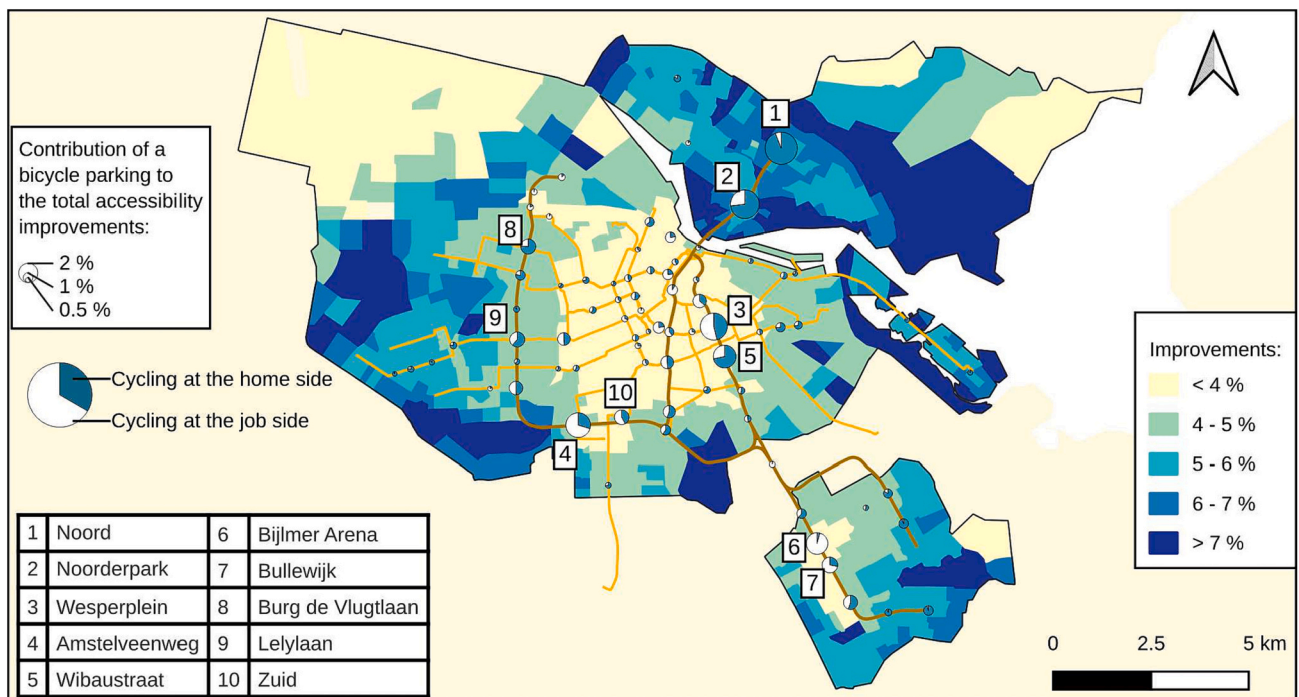


Fig. 4. Contribution of cycle-and-ride facilities in the total potential accessibility improvements.

Bottom right: distribution of accessibility improvements across the population.

When we enable the combination of cycling with transit, the accessibility improvements relative to the benchmark scenario are larger in neighborhoods outside of the city center and away from metro lines (top right of Fig. 3). These neighborhoods were also the ones with lower accessibility in the benchmark scenario. In these neighborhoods, cycling increases the access range and hence the number of reachable transit lines. Inhabitants living in the city center also benefit from combining cycling with transit, yet to a lower extent (their accessibility increases by around 3%). These individuals benefit mostly from cycling at the job side of their trips. Looking at the distribution of accessibility improvements across the population (bottom right of Fig. 3), we can see that all inhabitants benefit from the development of multimodal solutions, and there is a moderate difference in the magnitude of the accessibility improvements. Most inhabitants experience an increase in accessibility between 3 and 7%.

4.2. Contribution of cycling infrastructures in the total accessibility improvements

In this work, we assume that there are two necessary conditions for a multimodal trip alternative. There must be (1) a cycle lane between the origin and the destination of the cycling leg and (2) a bicycle parking at the transit stop (also called cycle-and-ride facility in this work). These infrastructures come at a cost, and quantifying the accessibility improvements resulting from each infrastructure allows local authorities to prioritize them. Using Eq. (19), we compute the marginal contribution of every bicycle parking and cycle lane to the overall accessibility improvements and show these in Figs. 4 and 5. We express these contributions in proportion to the total accessibility improvements. In Fig. 4, the pie charts represent cycle-and-ride parking facilities. Their size quantifies the increase in accessibility when cycling can be combined with public transport at that transit stop. The pie chart disaggregates further the accessibility gains between those resulting from cycling at the home side and those resulting from cycling at the job side of the trip.

For instance, a cycle-and-ride facility at the Amsterdam Noord metro stop contributes to 2% of the total accessibility improvements in the entire city and these improvements result mostly from enabling travelers to cycle from home to the stop.

In general, cycle-and-ride facilities at metro stops contribute the most to the overall accessibility improvements, followed by cycle-and-ride facilities at tram stops, as these two transit modes are faster and more frequent than buses and ferries. This is especially the case in the northern part of Amsterdam, only served by one metro line. Surprisingly, bicycle parking in the city center has a lower impact on accessibility than in the rest of the city, despite the high density of metro stops. In this area of the city, many streets are pedestrian, which results in lower cycling speed (see Subsection 3.3).

As for bicycle parking, cycles lanes serving metro stops contribute the most to the overall accessibility improvements (see Fig. 5). These cycle lanes are usually perpendicular to the metro lines they serve, connecting neighborhoods with a high density of jobs or population to the transit network.

One can also assess the impact of cycle lanes on accessibility at the neighborhood scale by zooming in on a specific location in Fig. 5 (see Fig. 6). This constitutes a great feature of our method, as it assists urban planners in delineating the cycle lanes at the street level. Fig. 5 shows two examples: Amsterdam Noord (left) and Bijlmer (right). Amsterdam Noord is residential and densely populated. Cycle lanes connecting most dense areas of the neighborhoods to the metro stop Noord have the largest impact on accessibility, and the bicycle parking at the metro stop would allow inhabitants living away from the line to cycle at the home side of trips. In contrast, Bijlmer concentrates jobs, and bicycle parking at the metro stop would enable travelers to cycle at the job side of trips. Cycle lanes would then connect the metro stop to locations with high job density. In both cases, the cycle lanes contributing the most to the accessibility improvements are perpendicular to the metro lines.

After measuring the contribution of each cycling infrastructure to the total potential accessibility improvements, we draw the cumulative distribution (see Fig. 7). The marginal accessibility improvements decrease with the number of cycling infrastructures installed. Few

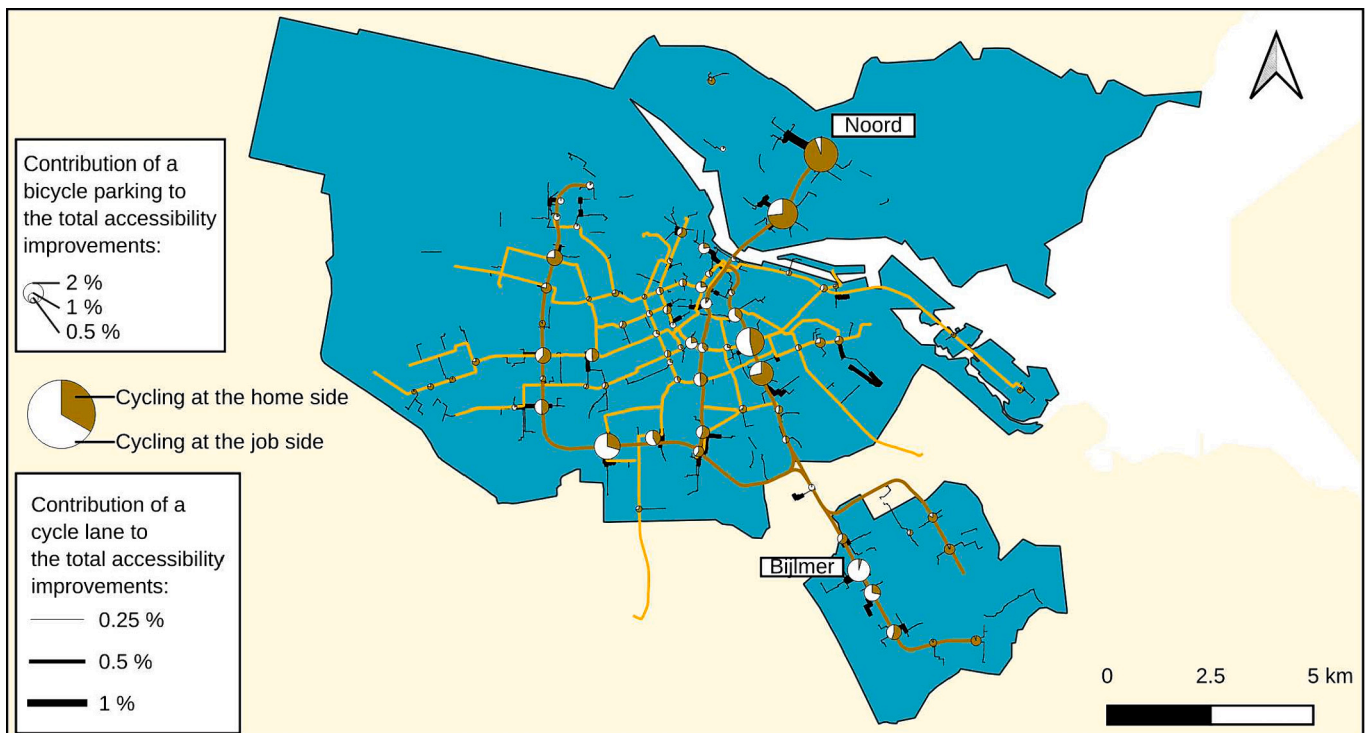


Fig. 5. Contribution of cycle lanes in the total potential accessibility improvements.

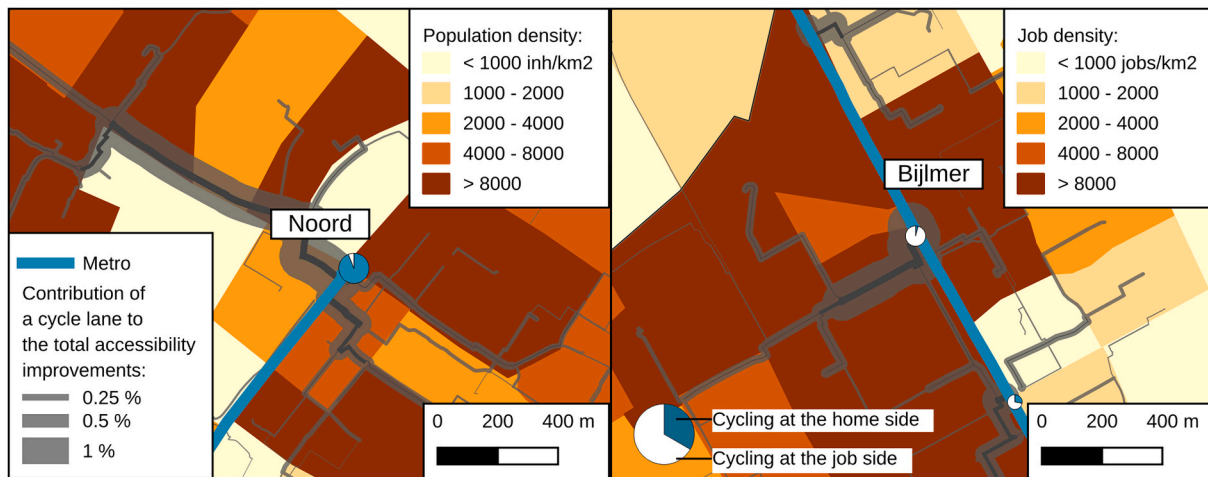


Fig. 6. Bottom left: Most relevant cycle lanes in Amsterdam Noord (left) and Bijlmer (right), in terms of accessibility improvements.

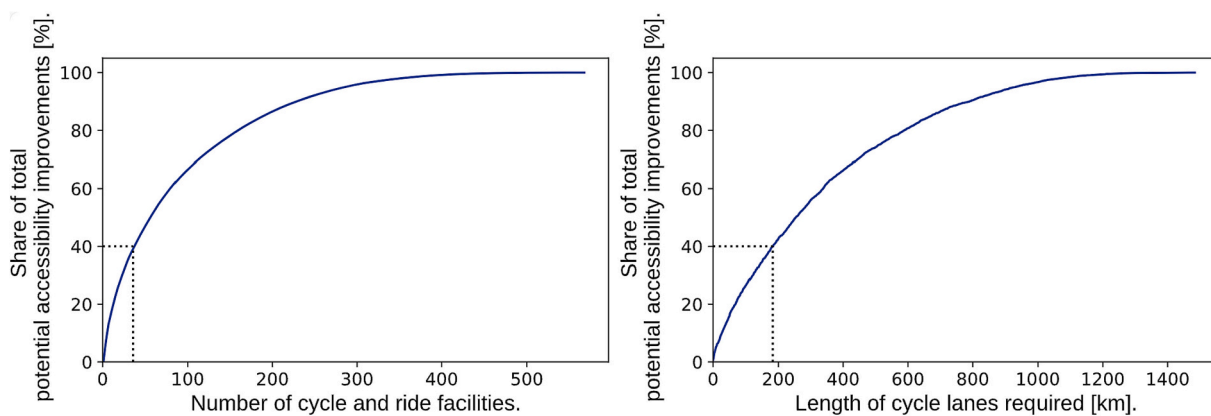


Fig. 7. Cumulative accessibility improvements due to cycle-and-ride facilities (left) and cycle lanes (right), expressed as a share of the total potential accessibility improvements.

Table 2

Contribution of the 10 most relevant cycle-and-ride facility to the total accessibility improvements.

| Stop name | Contribution to the total accessibility improvements | Stop name | Contribution to the total accessibility improvements |
|---------------|--|-------------------|--|
| Noord | 2.69% | Bijlmer Arena | 1.8% |
| Noorderpark | 2.40% | Bullewijk | 1.32% |
| Weesperplein | 2.25% | Burg de Vlugtlaan | 1.26% |
| Amstelveenweg | 2.06% | Station Lelylaan | 1.26% |
| Wibautstraat | 1.90% | Station Zuid | 1.23% |

stations and cycle lanes contribute to most of the accessibility improvements. In the Amsterdam case study, 40% of the accessibility improvements depend on 6% of the potential cycle-and-ride locations and 12% of the total length of potential cycle lanes (see Fig. 7). Hence, the top cycling infrastructures yield great returns. For instance, the top 10 cycle-and-ride facilities contribute to 18% of the total accessibility improvements (see Table 2). Such a table can help local authorities in planning effective multimodal solutions.

5. Discussion

In this work, we propose a method to quantify job accessibility improvements when cycling can be combined with transit. We contribute to the research in this field by two means. First, we propose a logsum-based indicator accounting for the traveler's perception of the different trip components (e.g. walking time, number of transfers...). Second, we measure the marginal contribution of any cycling lane or bicycle parking in the total potential accessibility improvements, which enables local authorities to prioritize multimodal infrastructures (see Subsection 5.1). We also identify three limitations in our approach and suggest directions for further research. First, the current approach does not allow to perform a cost-benefit analysis, while such an analysis is highly valuable for public authorities to relate potential accessibility improvements to cycling infrastructure cost. Second, one could explore other types of synergies between cycling and transit. Third, one could iterate over our method to consider equity aspects (see Subsection 5.2).

5.1. Benefits of the method proposed

The method proposed differentiates itself from the majority of accessibility studies, as it proposes a logsum-based indicator. Using such an indicator, we can weigh the different trip components to model the traveler's perception of these components from choice modeling theory (Ben-Akiva and Lerman, 1985). Our indicator has the following two advantages. First, we account for the burden for travelers to use a

bicycle. Dismissing it using a simple shortest-path approach would overestimate the accessibility improvements. Second, we model the traveler's decision for a mode (e.g. cycling, transit...) between an origin and a destination probabilistically. The traveler benefits from having multiple alternatives available at their disposal, instead of only considering the alternative with largest utility.

Our approach allows us to measure the accessibility improvements resulting from each single cycling infrastructure. This constitutes a great tool for public authorities as it can support them in defining priorities when developing cycling and multimodality alternatives in a city at the microscale. Our approach identifies the top locations for cycle-and-ride facilities and delineates the most suitable cycle lanes serving transit stops.

5.2. Recommendations for further research

In this section, we identify some limitations in our method and outline potential research opportunities related to those. Firstly, our method allows to estimate the potential gain in accessibility resulting from a given cycling infrastructure, but our method does not relate the gain to the monetary cost of such an infrastructure. Yet, this would enable public authorities performing a cost-benefit analysis and identify the cycling infrastructures that are worth developing. The logsum-based indicator could be used to this end, provided that one can monetize the benefit of being able to reach a certain job opportunity, and estimate the cost of cycling infrastructures.

Secondly, we treat cycling as a binary variable: it is either enabled or not by a cycling infrastructure, without considering its quality. In practice, the quality of the infrastructure impacts cycling experience and hence cycling usage. Further research could incorporate factors like the type of cycle lane (e.g. marked lane on the road or dedicated lane) or the continuity of the cycle lane, offering a more comprehensive perspective for urban planners and policymakers.

Thirdly, there exist other synergies between cycling and transit that go beyond the ones we model in this research. For instance, as bicycle use is highly sensitive to weather conditions, cycling could be used to partially substitute transit during favorable conditions. Under these circumstances, cycle lanes repeating the transit network may be as relevant as cycle lanes bridging discrepancies in the transit network. One could investigate these other synergies by designing a counterfactual scenario where travelers do not combine cycling with transit but may cycle to their job only if a transit alternative is also available. [van Marsbergen et al. \(2022\)](#) actually show that shared bicycles are more often used as a substitute for public transport than as an access/egress mode in the Dutch context.

Fourthly, we assume in this work that all inhabitants and jobs are equivalent, while social groups (e.g. age, education) may target different job opportunities, have diverging willingness to combine cycling with transit, and be unevenly distributed in space. Hence, our method does not ensure that the accessibility improvements are distributed fairly across different social groups in the city nor match the actual need of each social group. One could overcome such limitation by considering demographic variables in the utility function, provided that the travel behavior and the spatial distribution of the groups considered are known ([Shelat et al., 2018](#)).

5.3. Recommendations for practitioners

While this study presents a novel methodology to evaluate and enhance job accessibility through the strategic integration of cycling and transit infrastructure, its empirical findings are rooted in the specific context of Amsterdam. Practitioners looking to apply this methodology to other urban settings should adjust the logsum indicator to reflect the preferences and behaviors of a city's inhabitants.

First, this study focuses on certain trip attributes, and practitioners should not limit their analysis to these alone. Depending on the case

study considered, there may be trip attributes with a substantial impact on travel behavior that should be included, such as travel cost. The utility function should then be adapted to accommodate for additional attributes.

Second, the trade-offs residents weigh in between trip attributes may depend on the case study. For example, in a given city, residents might be willing to cycle longer distances to avoid transit transfers compared to those in Amsterdam. The utility function should therefore be calibrated for the case study considered, based on empirical data. Such data can be collected through a stated-choice experiment where subjects choose between a set of hypothetical travel alternatives, each comprising different values for trip attributes (e.g walking time, transit cost, cycling time...).

Selecting the appropriate utility function and estimating its parameters is key to adequately reflect inhabitants preferences before running the accessibility study.

6. Conclusion

Over the last decades, public authorities in many dense urban areas have voiced their intentions to shift from cars towards more sustainable modes such as public transportation and cycling ([Scheepers et al., 2014](#); [European Environment Agency, 2020](#)). Multimodal solutions contribute to this shift, opening up new travel alternatives between individuals and opportunities ([Tønnesen et al., 2021](#); [van Kuijk et al., 2022](#); [Montes et al., 2023](#)). In addition to contributing to the reduction of environmental emissions, it bolsters public health by encouraging physical activity ([Bassett et al., 2008](#); [Langlois et al., 2016](#); [Maizlish et al., 2017](#); [Ballo et al., 2023](#)). Yet, the lack of cycling infrastructure undermines the potential of multimodal solutions in cities. Developing such infrastructures is costly and practitioners need tools to identify which cycle lanes and bicycle parking to deploy first. The method we propose addresses this need as we quantify the job accessibility improvements resulting from specific cycle lanes and bicycle parking. We demonstrate how the method can assist policymakers and urban planners in developing multimodal solutions taking Amsterdam as a case study, where we identify the cycling infrastructures contributing the most to accessibility improvements. We hope that our method contributes to the development of multimodality, and eventually facilitates the transition towards more sustainable and livable cities.

Funding

This research was funded by the Amsterdam Institute for Advanced Metropolitan Solution.

CRedit authorship contribution statement

Lucas Spierenburg: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Hans van Lint:** Conceptualization, Resources, Supervision, Project administration, Funding acquisition. **Niels van Oort:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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