UNIVERSITY OF TARTU
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Analysis of Bicycle Sharing Data for Decision Support to Expanding Tartu Cycling Infrastructure

Master's Thesis (15 ECTS)

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Tartu 2024

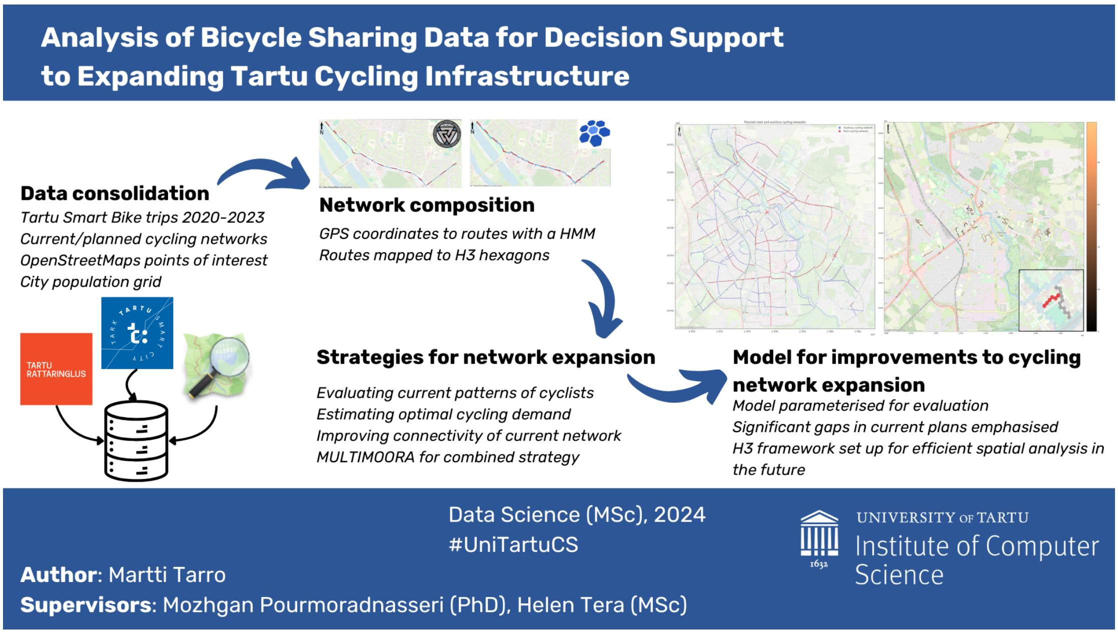
Analysis of Bicycle Sharing Data for Decision Support to Expanding Tartu Cycling Infrastructure

Abstract:

Public bicycle sharing systems have seen an increase in use across many cities in the world, and their expansion is partially dependent on the state of the infrastructure. Traditional road planning procedures rely on empirical evidence and surveys. The widespread availability of GPS data from micromobility sharing systems have seen the approaches enhanced by the analysis of movement patterns. Tartu has strategic plans for expansion of its cycling network to make the city as well as its surroundings more accessible by cycling. This thesis examines the patterns of Tartu Bike Share users using their geolocation data, and compares the planned networks to proposed paths from four strategies for prioritisation of new road sections. The strategies focus on evaluating current cycling patterns, estimating optimal paths, finding ways to make the current network more cohesive, and a combination of these strategies through MULTIMOORA modelling. The prioritised gaps from the model include multiple potential cycling paths, that had not been included in the planning of the main and auxiliary networks. The cycling network in Tartu is already expansive, but identifying significant gaps in the current and planned networks has the chance to improve it yet more.

Keywords: *Data science, network analysis, public bicycle sharing, infrastructure planning*

CERCS: P170 (Computer science, numerical analysis, systems, control)



Analysis of Bicycle Sharing Data for Decision Support to Expanding Tartu Cycling Infrastructure

Data consolidation

Tartu Smart Bike trips 2020-2023
Current/planned cycling networks
OpenStreetMaps points of interest
City population grid

Network composition

GPS coordinates to routes with a HMM
Routes mapped to H3 hexagons

Strategies for network expansion

Evaluating current patterns of cyclists
Estimating optimal cycling demand
Improving connectivity of current network
MULTIMOORA for combined strategy

Model for improvements to cycling network expansion

Model parameterised for evaluation
Significant gaps in current plans emphasised
H3 framework set up for efficient spatial analysis in the future

Data Science (MSc), 2024
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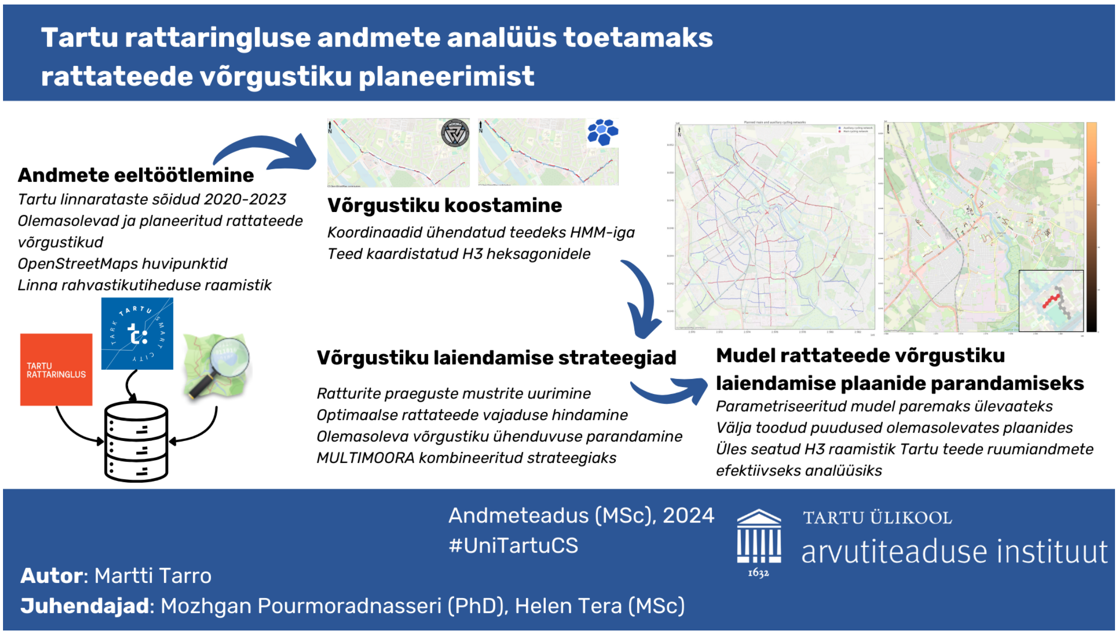
Tartu rattaringluse andmete analüüs toetamaks rattateede võrgustiku planeerimist

Lühikokkuvõte:

Jalgrataste ühiskasutussüsteemide kasutamine on paljudes maailma linnades suurenenud ja nende levik sõltub osaliselt infrastruktuuri seisundist. Traditsioonilised teede planeerimise protseduurid tuginevad empiirilistele tõenditele ja uuringutele. Tänu mikroliikuvuse jagamise süsteemide GPS-andmete laialdasele kättesaadavusele on lähenemisviise täiustatud liikumismustrite analüüsiga. Tartul on strateegilised plaanid jalgrattateede võrgustiku laiendamiseks, et muuta nii linn kui ka selle ümbrus jalgrattaga paremini ligipääsetavaks. Käesolevas töös uuritakse Tartu rattaringluse kasutajate asukohaandmeid ja võrreldakse planeeritud võrgustikke nelja strateegia pakutud teedega uute teelõikude prioriseerimiseks. Strateegiad keskenduvad praeguste jalgrattasõidumustrite hindamisele, optimaalsete radade hindamisele, võimaluste leidmisele praeguse võrgustiku sidusamaks muutmiseks ja eelnevate strateegiate kombineerimisele MULTIMOORA mudelis. Tähtsuse järgi järjestatud teelõikudes on mitu potentsiaalset jalgrattateed, mis ei sisaldu praegustes põhi- ja abivõrkude plaanides. Tartu jalgrattateede võrgustik katab juba praegu suure ala, kuid oluliste lünkade tuvastamisel praeguses ja kavandatavas võrgustikus on võimalus seda veelgi parandada.

Võtmesõnad: *Andmeteadus, võrgustike analüüs, rattaringlus, infrastruktuuri planeerimine*

CERCS: P170 (Arvutiteadus, arvutusmeetodid, süsteemid, juhtimine (automaatjuhtimisteooria))



Tartu rattaringluse andmete analüüs toetamaks rattateede võrgustiku planeerimist

Andmete eeltöötlemine

Tartu linnarataste sõidud 2020-2023
Olemasolevad ja planeeritud rattateede võrgustikud
OpenStreetMaps huvipunktid
Linna rahvastikutiheduse raamistik

Võrgustiku koostamine

Koordinaadid ühendatud teedeks HMM-iga
Teed kaardistatud H3 heksagonidele

Võrgustiku laiendamise strateegiad

Ratturite praeguste mustrite uurimine
Optimaalse rattateede vajaduse hindamine
Olemasoleva võrgustiku ühenduvuse parandamine
MULTIMOORA kombineeritud strateegiaks

Mudel rattateede võrgustiku laiendamise plaanide parandamiseks

Parametriseeritud mudel paremaks ülevaateks
Välja toodud puudused olemasolevates plaanides
Üles seatud H3 raamistik Tartu teede ruumiandmete efektiivseks analüüsiks

Andmeteadus (MSc), 2024
#UniTartuCS

TARTU ÜLIKOOL
arvutiteaduse instituut

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Contents

1 Introduction

Cycling as a means for urban transportation has significant environmental, economic, and health benefits [CKR+08]. Strategies to encourage its expansion include various strategies, of which successful ones integrate transport planning initiatives and effective land use [BD16]. At a time when technological advances have made data more abundant than ever, decision-making processes require consolidation of data from multiple sources for transparency and objectivity in prioritisation of resources.

The city of Tartu has four strategic goals for the cycling traffic by 2040 [Con21]. The first, focusing on the end result, is to decrease the number of cars in traffic (mostly at peak hours) to improve the air quality and noise levels. The second, prioritising the client, is to increase the number of cyclists, decrease the number of sick days through improving people's health, increase the satisfaction of cyclists, and increase the number of students using bicycles. The third goal focuses on the processes of infrastructure maintenance, to increase the average speed and safety of cyclists, increase the number of cyclists in the winter as well as the number of days when bike paths are safely rideable. The final goal for planning and construction of the necessary infrastructure emphasises the availability of bicycle parking near places for work, study, and living, the expansion of bicycle-only paths to areas of interest outside of Tartu, and the requirement to define the interests of cyclists before planning and projecting bicycle paths. The current thesis could provide input for the final goal by examining the current patterns of cyclists in Tartu.

Tartu has plans for the expansion of its bicycle path network, with the main network to be built by 2027 [lin23]. The planned main cycling network of Tartu aims to connect districts at the edge of the city to the centre or serves to improve traffic between districts next to one another [Gov21]. The auxiliary network aims to make the main network more dense, improving connectivity and accessibility, and mainly serving to improve traffic within the districts.

The current cycling network in Tartu, visualised in figure 1, is defined with road types of **light traffic paths** ('jalg- ja jalgrattateed'), **bike paths** ('jalgrattarada'), and **bike roads** ('jalgrattatee'), and it covers 190 km of the 635 km of all light traffic roads in Tartu. 175 km of the cycling network consists of light traffic paths, meaning it is meant for both pedestrians and cyclists, of which 12.4 km are noted to be paths that are bike roads marked on the driveways, and 15 km are classified as either bike roads or bike paths. Unfortunately, Tartu city open data does not have further separation of the light traffic paths to detect which paths meant for both pedestrians and cyclists have a separation line. This kind of separation is important for the safety of both groups, so it is a significant limitation for detecting paths meant only for cyclists.

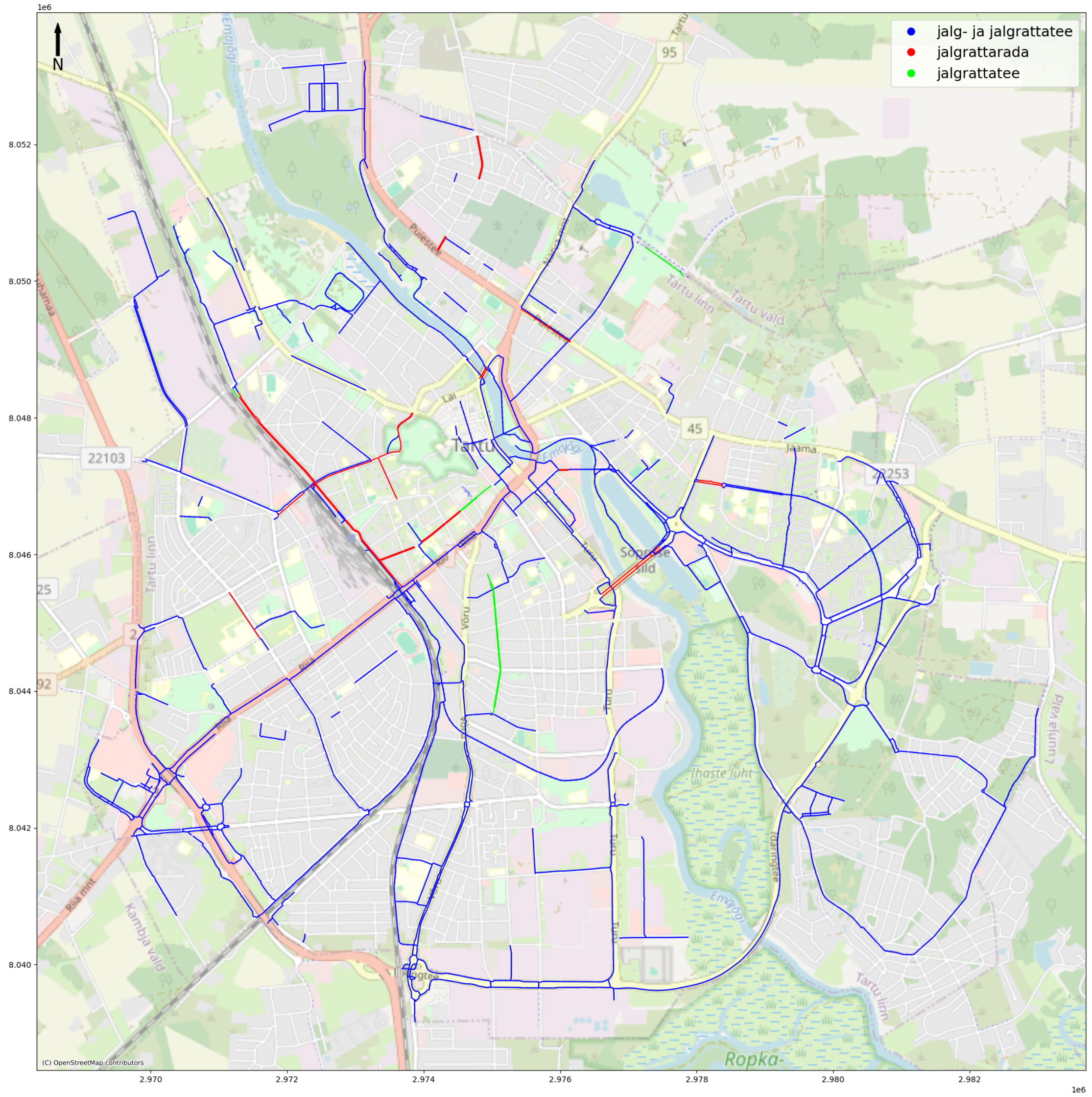


Figure 1. Current cycling network based on road types

While the current cycling network expands to most corners of Tartu, roads within and between districts could still be improved. This thesis focuses on finding these gaps.

1.1 Research objectives

The objective of this thesis is to provide Tartu city governance input with regard to the prioritisation of bicycle lane planning, examining the current and planned cycling networks, estimating the optimal bicycle lane usage, and constructing a more cohesive network. The final goal is to identify the most significant gaps in the network through different strategies for its expansion.

Areas in Tartu that lack designated cycling infrastructure have been previously researched [Ter22], which gave an overview of the dynamics of Tartu Smart Bike, suggested new locations for its stations, and identified road segments with an average of more than 1000 monthly trips. This thesis aims to expand on this research, as well as utilise network analysis methods proposed by Zhao and Manaugh [ZM23], to identify road segments which are not included in the current plans of the cycling networks.

1.2 Thesis structure

The sections in the thesis are divided as follows:

- Section 2 describes the findings of previous studies on map matching methodologies, the expansion of road networks, as well as prioritisation strategies for them, and gives an overview of the study area.

- Section 3 outlines the datasets, and employed methodologies for map matching geolocation data, and cycling network expansion prioritisation.

- The methodologies for cycling path prioritisation are described in section 4, where the first subsection examines the current as well as planned cycling networks. The following three subsections outline the employed strategies, which focus on current cycling demand evaluation, potential demand estimation, and connectivity improvements. The final subsection proposes a methodology for a combination of the three strategies.

- The gaps in the current as well as planned cycling networks, derived from the combined strategy, are discussed in section 5. The section additionally identifies the significance of the models, and their possible improvements.

- Finally, section 6 summarises the insights from this thesis.

2 Background and related works

This section gives supporting information on previous works, which are related to the thesis. Subsections 2.1 and 2.2 provide an overview of the public bicycle sharing systems in general, and specifically in Tartu. The following subsections 2.3 and 2.4 describe the different map matching methodologies, and the H3 hexagonal system in particular. The final subsections 2.5 and 2.6 expand on previous studies, which discuss the gaps in cycling networks, and their prioritisation.

2.1 Bicycle sharing systems

Public bicycle sharing systems (PBSS) have seen an increase in popularity in cities around the world as a response, in the case of city planning, to car-centric transportation systems. Cycling as a solution of efficient mode of sustainable urban transport is more economic and wide-ranging than solely focusing on motor vehicle electrification [BDAB$^+$21]. This has increased the need for infrastructure that supports micromobility, which includes bicycles as well as the recently popularised e-scooters.

PBSS can be grouped into four generations - white bicycles, coin-deposit, IT-based, and demand-responsive systems, with the last of them being the main system in current use, which can be further divided into docking and dockless systems [ZGS$^+$22]. Docking systems allow the user to rent a bike from a dock, and return it to another dock within the system. The docking stations serve as nodes for renting and returning bicycles. The more recent dockless systems rely on smart technology to be independent of stationary docks. In these systems, bicycles can be rented and returned anywhere within a designated area, providing greater flexibility for the users.

2.2 Tartu Smart Bike

Tartu Smart Bike is a docked self-service PBSS mainly aimed for short rides, with the first hour free for periodic passes, that was introduced in 2019 [oT24a]. As of the beginning of 2024, it has more than 750 bicycles, of which two thirds are e-bikes, 102 stations, of which 88 are within city limits, and roughly 25 thousand users, which is around a quarter of the population of Tartu. The number of available bikes in the winter is reduced, since e-bikes are stored when the temperatures drop below freezing. The PBSS is easily accessible to all who want to use it, with new users requiring registration through a mobile app or the website, and existing users can access the bikes using the same methods, or using various cards including bus cards in Estonia, and ISIC. An important consideration when examining the cycling patterns in Tartu, is that the trips on shared bicycles only account for around 20-30% of the total bicycle usage in Tartu, but Tera *et al.* estimate that these trips are representative of the overall bicycle path usage [TPH23].

2.3 Map matching methodologies

Map matching methodologies can be divided into four main categories: geometric, topological, probabilistic, and advanced methods [MWL24]. Geometric methods focus on the best-fitting geometric representation, encompassing Euclidean distance as well as closeness through various metrics. Topological methods concentrate on the connectivity and the relationships between road segments, using attributes of the network for improved matching algorithms. Probabilistic methods, such as Hidden Markov Models, treat each GPS point as an observation, with each road segment with a path as the true hidden state [MWL24]. Previous years have shown some new advanced map matching methodologies being proposed, e.g. machine learning techniques, or utilisation of a combination of previous method categories.

Schweitzer *et al.* proposed an efficient buffer-based map-matching procedure for detecting bicycle paths, which added a buffer around the edges of the network to find the route with the lowest cost [SBR16]. In previous analysis of Tartu road networks, Tera used the methodology of Yang *et al.*, which determines the route based on the trajectory of the movement [YTZL18]. Of the more recent studies, Saki and Hagen built a framework called Valhalla, which uses a Hidden Markov Model to estimate the probabilities of the consecutive points in a route to belong to a section of the road [SH22]. The current study uses the Valhalla framework to construct routes from sparse coordinates.

2.4 Hexagonal grid system

The H3 hexagonal grid is a hierarchical, open-source geospatial indexing system, which was created by Uber in 2018. It was designed for clustering micromobility GPS coordinates into spatial cells to estimate route usage frequency at the desired resolution [Bro24]. Using a hexagonal grid over a rectangular one offers multiple advantages. Curvature of the Earth introduces distortions to every spatial matching grid system, but a hexagonal structure reduces that effect. In addition, route planning requires movement between cells, meaning additional edges to the cell allow for more flexible movement. The hierarchical structure of the system enables the user to adjust the resolution of the observed cells based on availability of data.

H3 hexagons have previously been used for a multitude of different tasks. Amudha *et al.* matched the taxi demand to the grid, to predict future demand using an LSTM [ABGSK23]. Woźniak and Szymański aggregated OSM tags for hexagons in different cities to train a model for identifying map characteristics at different resolutions [WS21]. OSM data was also used by Raczycki and Szymański to predict bicycle sharing stations using transfer learning [RS21]. Looking at using micromobility data, Agrawal *et al.* used H3 to form a spatial histogram of a GPS scooter database, where the trip was logged every 6-8 seconds [APP23]. With the consideration of a small time window between coordinate logging, and the high resolution of 13 used, the coordinates were not map matched to include cells, which might have been used in the logging gap. The network composed from the cells was used to propose an algorithm for finding the shortest path between nodes.

2.5 Cycling network growth

The expansion of cycling networks has recently been approached from multiple angles. By examining the structure of synthetic bicycle networks, Szell *et al.* explore three growth strategies for network expansion, focusing on increasing betweenness, closeness, or a randomised approach [SMP$^+$22]. The study emphasised the importance of choosing the right growth strategy and consistent investments to surpass short-term deficiencies until a critical mass of roads has been achieved. GPS traces of bicycle trips have been used for estimating the potential demand and constructing a cycling network in Bogota, Colombia [OTV$^+$20], utilising percolation analysis to identify potential paths with a length of more than 50 meters between existing bike paths. Most studies, however, have not considered realistic constraints such as budget limitations, construction convenience, and bike lane utilisation. These areas have been explored and tested in Shanghai, China [BHR$^+$17], and Montreal, Canada [ZM23].

2.6 Network expansion prioritisation

The planning of infrastructure expansion requires input on the specific roads to prioritise, for which various models have been suggested. Liu *et al.* proposed a multi-criteria based ranking system for road projects, which took inputs from expert opinions and project feasibility study, and weighted the criteria based on a public survey [LBWPM15]. Some models aim to fix the problem of individual projects' effects on the overall road network. Novak *et al.* achieved that through a custom network-based performance metric, utilizing network topology, connectivity, and the dynamic rerouting of traffic on roadway links [NSS12].

The current thesis focuses on network expansion at a smaller scale, examining cycling road networks. Beukes and Vanderschuren employed a K-means clustering on the spatial centroids from multi-criteria analysis of land use, as well as socio-economic, environmental, and transportation criteria [BV12]. Zhao and Manaugh proposed three strategies for network expansion, focusing on network consolidation for improving connectivity, accessibility for transportation-disadvantages population, and reducing greenhouse gas emissions of the transportation sector [ZM23]. While their strategies focused on multiple positive aspects of the cycling network not previously studied, they did not analyse the actual demand of cyclists, which is what the current study aims to improve upon.

3 Data preprocessing

The datasets used consisted of the datasets of Tartu Smart Bike Share system from 2020 to 2023, as well as the Open Street Maps (OSM) data for points of interest, and Tartu GeoHub data of the current network as well as the city plans for its expansion. Although the bike sharing system was started in June 2019, the data for that year is not included in this analysis, since the initial months introduced uncommon patterns in usage, with the system being free for use in the initial months. The code used for analysis can be found in a private GitLab repository upon request [rep24].

- **Tartu Smart Bike stations.** The stations dataset was acquired from the Tartu GeoHub API of the current stations, and was expanded with historical stations gathered from Intelligent Transportation Systems (ITS) Lab. The total number of stations, including historical stations, was 102, with 88 within the city limits.
- **Tartu Smart Bike locations.** Locations dataset contains the recorded latitude and longitude of the bicycles with an identifier for the trip, totalling nearly 330 million data points. The GPS coordinates had been recorded with an interval of 5 seconds for 5 times, following a pause of 40 seconds. The gap in the measurements necessitated the usage of map matching methods, to get a comprehensive overview of the bicycle location during the whole trip.
- **Tartu Smart Bike routes.** Routes dataset contains information regarding the origin and destination of the trip, as well as data about the specific bicycle and the user, although only the former data was used in the current thesis. The total number of trips was nearly 3 million over 4 years.
- **Current and planned cycling networks.** The cycling networks were acquired from Tartu GeoHub API, which consist of the current pedestrian and cycling roads, and describe the roads' properties. The cycling network to be analysed was defined to include only roads with the labels related to bicycles - cycling road ('jalgrattatee'), pedestrian- and cycling road ('jalg- ja jalgrattatee'), and bike path ('jalgrattarada'). The planned networks contain only the planned cycling paths, divided into main and auxiliary networks, visualised in section 4.1. Their purpose was explained in detail in section 1.
- **OSM points of interest.** Data for the points of interest was extracted from OSM using Overpass API, limiting the search to the city borders of Tartu, extracted from OSM as well. Points of interest included the types of destinations most relevant to the general population: groceries, pharmacies, hospitals, schools, and kindergartens [ZM23], with the addition of university buildings, considering their importance in Tartu, since around 17 thousand people work for University of

Tartu [oT24b]. Points of interest with the same category that shared a border, e.g. the different sections of Maarjamõisa hospital, were joined to one polygon. The locations of the points of interest are visualised in appendix I.

3.1 Scope of the study

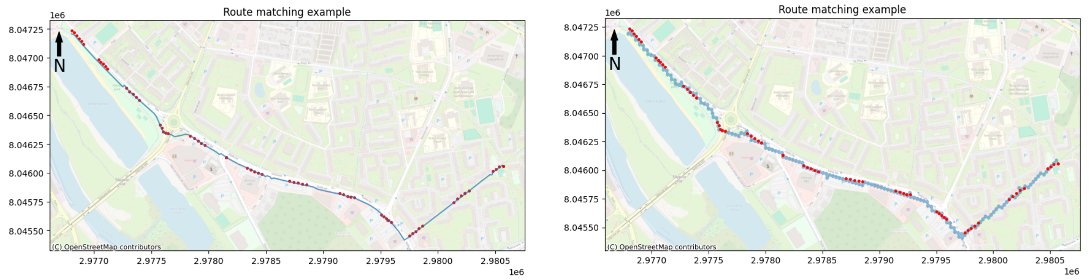
Since the aim of this thesis is to examine the bicycle network in Tartu, the bike trips, as well as the current network to be analysed, were limited to the city borders. The GPS coordinates and routes datasets were filtered after the map matching process to include road segments, where the user had exited the city before the final recorded coordinates. A limitation in the study is that the coordinate dataset to be analysed contains data only for the users of Tartu Smart Bike, as mentioned in subsection 2.2.

3.2 Map matching geolocation data

In order to construct a complete route from the set of coordinates in the dataset, a map matching service API in the Valhalla Python library was used. Valhalla is an open source routing engine primarily written in C++, usable under the MIT license, which uses OSM tiled data structure for various routing and navigation tasks [val24]. The map matching service allows for sequential coordinates of a bike trip to be mapped onto OSM roads and paths. While the recommended trace point density of one point per one to ten seconds could not be matched, the gaps in the GPS data did not disallow most paths to be matched, with only 187 trips discarded of nearly 3 million total trips in 330 million data points.

Route tracing was done using mostly the default parameters, with the differences in using the bicycle costing model, map snapping as shape matching, and a breaking distance of 3000 meters as an additional trace option. In addition, routes with less than 3 points were not considered for model optimisation. Bicycle costing model has a slight preference for using cycleways or roads with bicycle lanes [val24]. A limitation for this methodology lies in that the regular gaps in the GPS coordinates for a route are around 40 seconds, which could result in a bike path being matched for a trip, while the actual route taken could have been on a sub-optimal path.

Map snapping algorithm was applied for raw GPS data as seen in the example of figure 2a, since it is to be used in cases where the input shape might not closely match Valhalla edges. Breaking distance sets the limit for the distance two successive points can be apart for them to not be considered connected. The breaking distance was set for 3000 meters to not discount trips with missing data points.



(a) Matching coordinates with Valhalla (b) Matching linestrings to H3 (resolution 12)

Figure 2. Example of map matching

3.3 H3 for network analysis

Constructing a cohesive network from the map-matched routes of the GPS data based on the linestrings, calculated from the coordinates in the datasets, introduces multiple challenges. The starting and ending coordinates of the linestrings do not always connect to other linestrings as expected, leaving a gap at an intersection or for two sides of the road. An initial approach for constructing a network after matching coordinates to the roads in OSM introduced many components with unmatched gaps.

This thesis proposes using H3 hexagons as a framework for the purposes of network analysis, following the example of Agrawal *et al.* [APP23], with the difference of using a lower resolution of 12 instead of 13. Resolution was chosen based on initial comparisons between the current network and map matched geolocation data, and with the consideration of hardware limitations in calculating the potential paths. The trips were matched to the H3 hexagons using line tracing in module of H3Pandas, as seen in figure 2b. The average cell area was 245.011 m^2 (stdev 0.115) with an average short diagonal length of 23.786 m (stdev 0.005). The length of the short diagonal, or the distance from an edge of the cell to the opposing edge, is used to estimate the distance between two cells, and from this, the length of the proposed paths.

4 Analysis

This section is divided into five parts - examining the current cycling network, three strategies for evaluating its expansion, and combining the results to identify the most significant gaps. The three proposed strategies give corresponding insights into the current users' usage patterns, estimate the optimal cycling demand between bike sharing stations, and improve upon the connectivity of the current cycling network.

4.1 Current network

The current cycling network, initially stored in linestrings formed from sets of coordinates, was matched to H3 hexagons. A problem with finding gaps in the current network, is that in many cases, the algorithms for finding the gaps in the networks cannot account for situations, where a proposed path is parallel to the path in the current network. This might be due to inaccuracies in map matching, or not using the current cycling infrastructure. Such occurrences were identified on most roads with cycling infrastructure. Figure 3 shows the current network with an example of the problematic cells.

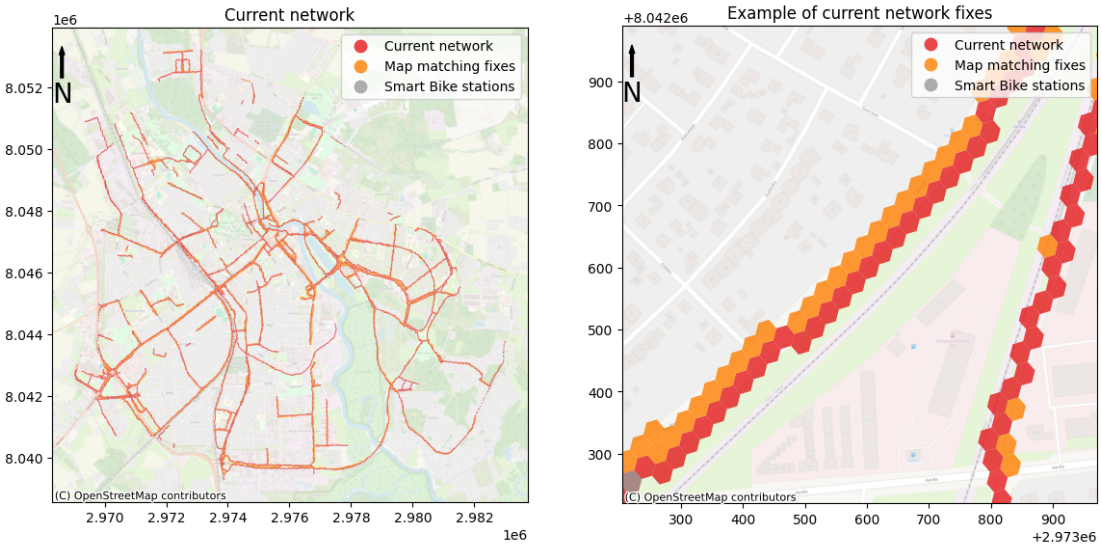


Figure 3. Current cycling network with fixes for parallel paths, and an example of matching algorithm's results.

Potential cells to be added to the network were devised from the hexagons in the map matched GPS coordinates dataset, and the predicted routes between origin and destination stations. A map matching fix algorithm was applied to account for the parallel paths as follows:

1. For each proposed cell, the number of neighbouring cells from the current network was calculated.
2. The proposed cell was added to the current network if it had at least 3 neighbouring cells in the current network.
3. Steps 1 and 2 were repeated until the proposed cells had a maximum of 2 neighbouring cells in the current network.

The iterations of fixes yielded a total of 4126 additional cells, as shown in table 1. Since the aim of this thesis is to improve connectivity of the cycling network, the cells with current bike sharing stations were added as parts of the network as well.

Iteration	**Network size**	**Added cells**
Initial network	8430	0
Iteration 1	10550	2120
Iteration 2	11480	930
Iteration 3	11946	466
Iteration 4	12195	249
Iteration 5	12349	154
Iteration 6	12430	81
Iteration 7	12485	55
Iteration 8	12516	31
Iteration 9	12537	21
Iteration 10	12546	9
Iteration 11	12551	5
Iteration 12	12555	4
Iteration 13	12556	1
Iteration 14	12556	0
Bike stations	12644	88

Table 1. Current network fixes

The map matching fixes introduced cells to the network, adding up to 49% of the size of the initial network. While this is a significant expansion of the network, it did not affect the structure of the network. The fixes assisted in removing inconsequential cells from consideration for future paths, since they parallel the existing paths.

The strategies in the following subsections were used to find optimal routes to add to the current network. As Tartu already has its own plan for network expansion, the proposed routes were compared to the existing plans to find road sections outside of them. Figure 4 shows the planned main and auxiliary networks within city limits, excluding the current network. The plans for the main network expand outside city limits as well, but the current analysis focuses only on paths within the city.

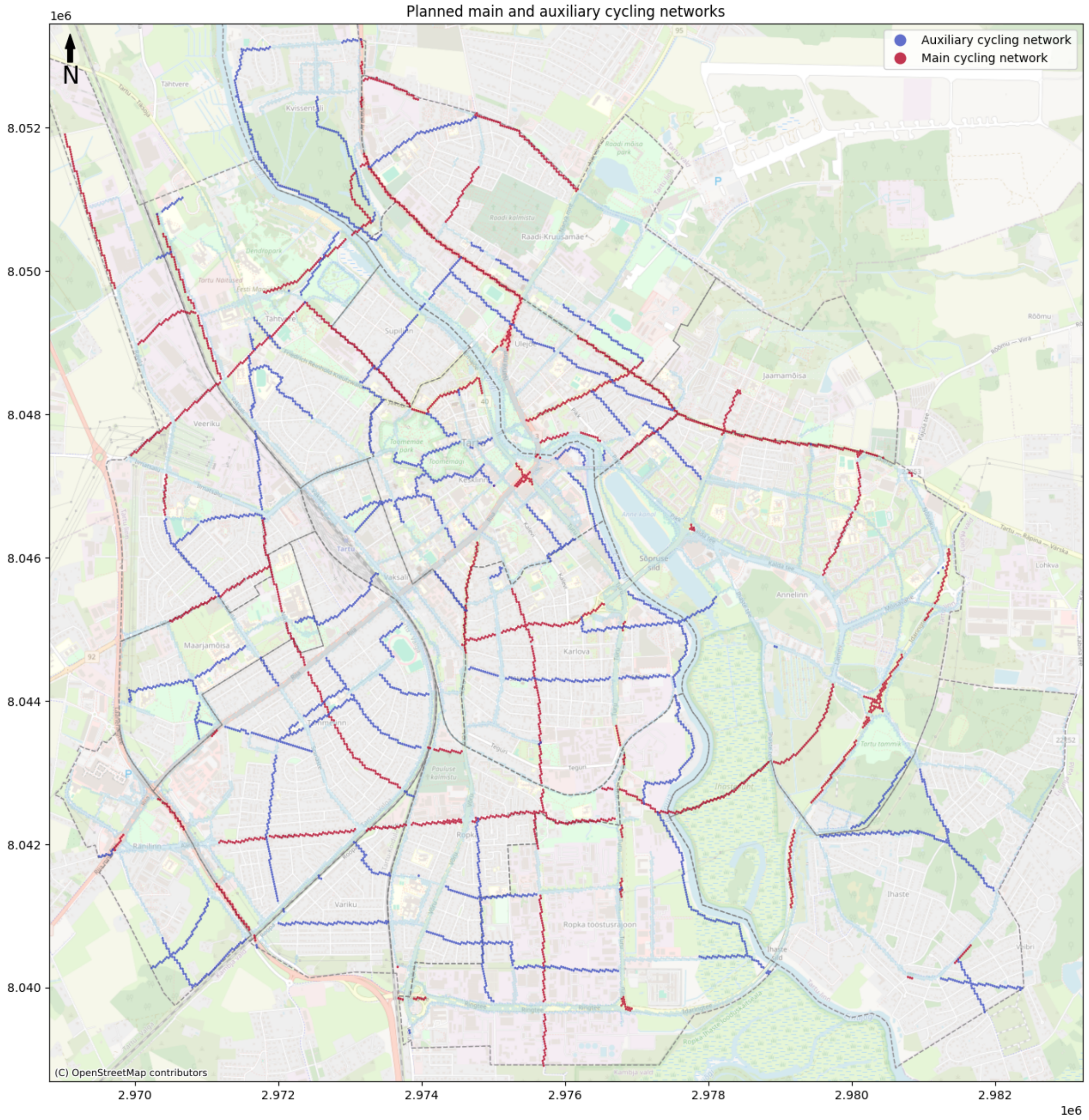


Figure 4. Planned main and auxiliary cycling networks

4.2 Evaluating current demand

Identifying paths most used by cyclists, but not in the current network, reveals sections that are in active use, despite lacking the proper infrastructure to support it. Improving upon these gaps in the network can help with user engagement, as well as improve the

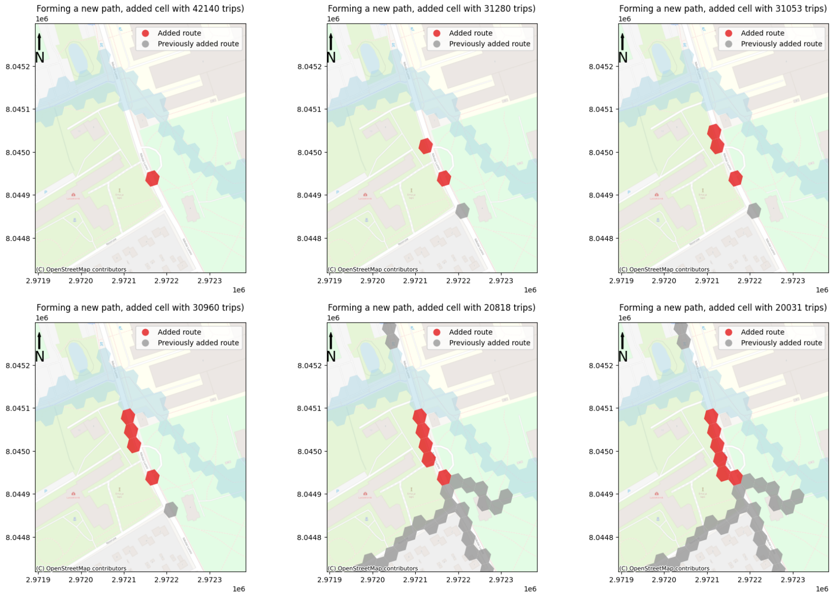


Figure 5. Example of forming a path

safety of cyclists as well as pedestrians. The first strategy focused on evaluating the current demand of the cyclists, examining the map matched geolocation data.

Adding the cells to the network as road segments that connect parts of the existing network was done in the following iterative steps, illustrated in figure 5:

1. Cells within the current network were excluded.
2. Cells were ranked based on the number of trips that crossed the cell.
3. A set of adjacent candidate cells are being added to the network, if they have at least 2 neighbours in the current network (origin and destination), with the set being reduced to the shortest path between them to minimise the number of cells in the proposed road segment.
4. A route was added to the current network if it was composed of at least 3 cells, which equates to around 74 meters. The aim was to exclude very short routes, which give little information on the significant gaps in the network.
5. Steps 1 to 5 were repeated until a set limitation of number of paths or total length of the paths added.

The algorithm is more computationally expensive the more routes are added, since the number of cells, without connections to the current network, increases exponentially for higher iterations. For the purposes of this thesis, the iterations were limited to identify paths adding up to a length of 100 km.

A map of the proposed paths to be added to the current network is shown in appendices II and VI. Comparing the proposed paths to the planned networks, as illustrated in figure 6 in groups of 25 km of paths, revealed some paths for which the current plans do not account. While the main goal of the main planned network is to improve connections between districts and outside the city, the auxiliary network connects paths within districts, hence the gaps emphasised by this strategy could be considered in the latter.

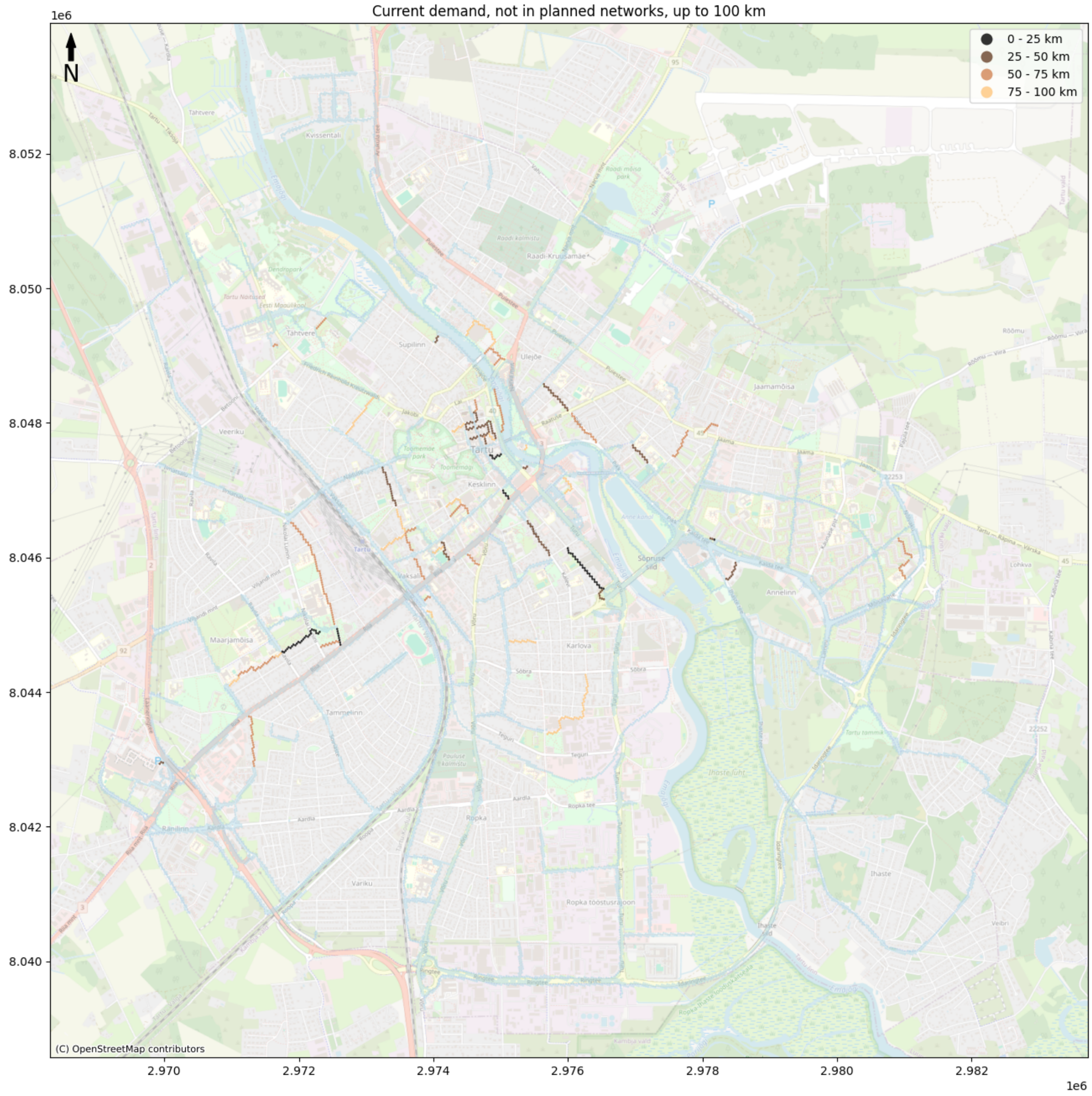


Figure 6. Road segments that are not part of the planned networks, evaluated by examining current demand

4.3 Estimating potential demand

Evaluating gaps in the network from the current demand of cyclists of Tartu is influenced by the quality of the infrastructure, among other factors. To overcome this bias, the second strategy estimated the cycling demand irrespective of the current cycling paths by finding the optimal routes between pairs of stations. This was achieved by calculating the shortest paths between the origin and destination stations, for trips with different origins and destinations, using Valhalla's routing API with the costing option for pedestrian traffic.

This strategy has an important simplifying assumption that most bike share trips aim to get from one station to the other. While this may not be the case for all trips, the share of round trips over the 4 observed years was around 9%. For the purposes of optimisation, the origin-destination combinations were limited to have at least 10 trips for each of the examined year between 2020-2023. This limited the number of combinations from 6137 to 5590. The shortest path between the two stations was calculated for each origin-destination combination, with the resulting paths converted to H3 hexagons and number of trips summed to get the total predicted trips per cell. Finally, the routes were prioritised in the same five steps as in the evaluation of the current demand in section 4.2, limiting the total length of the proposed sections to 100 km.

The proposed paths across Tartu are shown in appendices III and VII, and in figure 7, which show most of the higher priority paths near the city centre. The most significant gaps are discussed in the subsection 5.2.

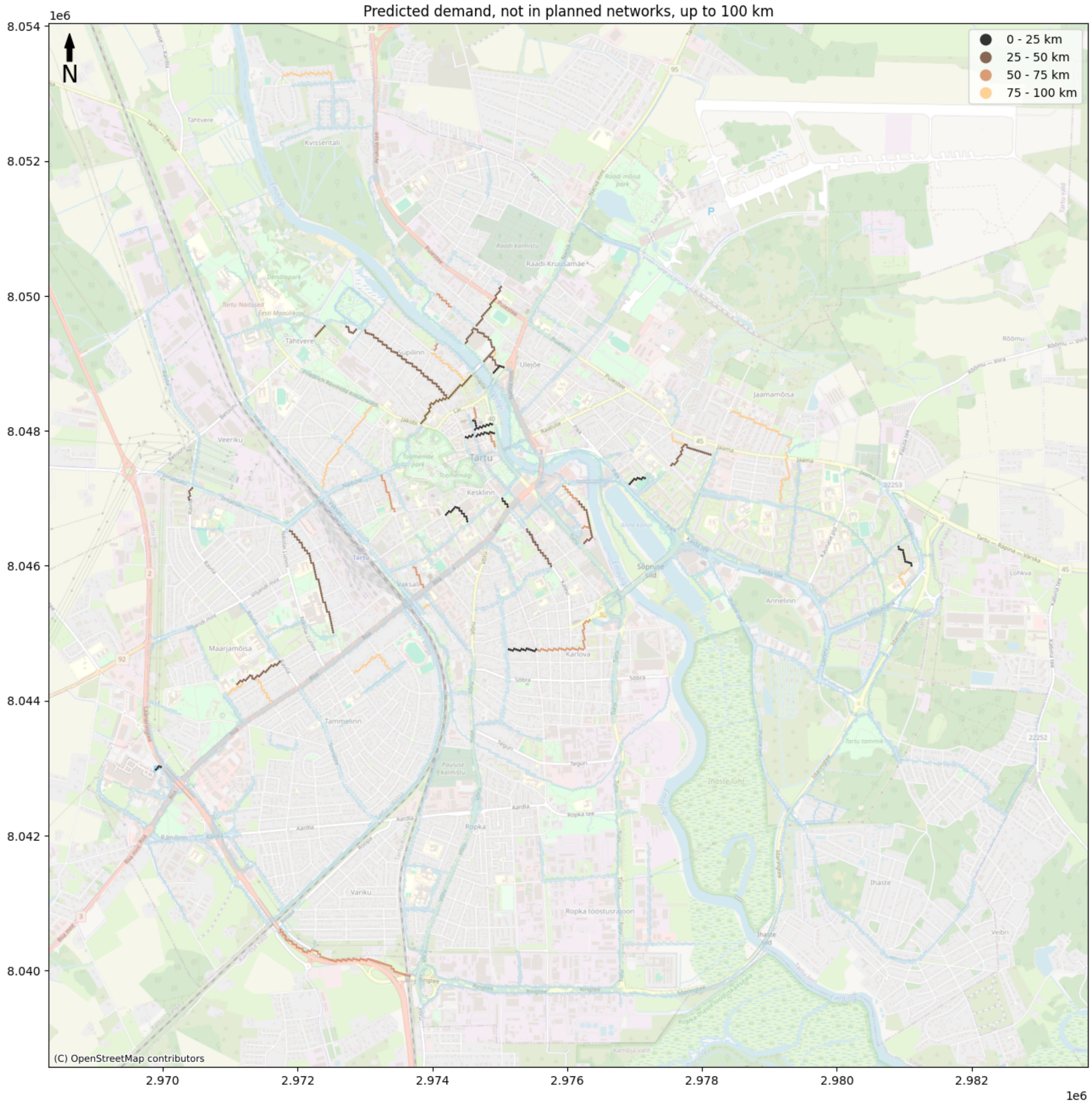


Figure 7. Road segments that are not part of the planned networks, evaluated by estimating potential demand

4.4 Network connectivity

The current cycling network in Tartu, matched to H3, consists of 8430 nodes, and 10362 edges between them. While the fixes described in section 4.1 were useful for optimising the algorithms used for finding the shortest path between different parts of the network, they were not used for the current strategy. The network was expanded with the public bicycle sharing stations, within the city limits, to improve connectivity not only between components in the network, but the bike share system as well. The initial network was divided into 29 components, with the largest component comprised of 7760 nodes, or 92% of the network. After adding the stations to the network, the network was expanded to 62 components with 7792 out of 8490 nodes.

The final applied strategy, to improve network connectivity, differs from the previous ones in that it does not rely on the actual Smart Bike usage data, but the structure of the network. It focuses on constructing a cycling network, where each path can be accessed from anywhere in the network, with the paths to be prioritised chosen based on their proximity to the points of interest to the potential user, as clarified in section 3. The distribution of the points of interest are described in table 2 and visualised in appendix I.

POI type	**Query selector**	**POI count**
school	"building"="school"	34
kindergarten	"building"="kindergarten"	30
groceries	"shop"="supermarket"	29
university	"building"="university"	22
groceries	"shop"="mall"	13
pharmacy	"amenity"="pharmacy"	4
hospital	"amenity"="doctors"	2
hospital	"building"="hospital"	1

Table 2. Points of interest from OSM

The third approach is based on the first strategy used by Zhao and Manaugh [ZM23], which aims to improve the connectivity of the bicycle network, with the highest priority on the parts of the network with the most points of interest (POI) in the vicinity. Connecting the components was done in five steps:

1. The current cycling network is map matched to H3 hexagons (resolution 12) to compose a network of polygons.
2. Network components are ranked by the number of POIs within a walking distance of 500 meters of any of the nodes in the component. The walking distance is calculated using the routing service API of Valhalla.
3. The two components of the network with the largest POI coverage are identified as the highest priority to be connected.
4. The shortest path between the two components is calculated in two steps.
   (a) The initial distances between the nodes in source and target components are calculated using the matrix API. Due to the API's limitation of a maximum

    of 2500 source or target locations to be used, a naive implementation of Euclidean distance is applied before the matrix calculation, limiting the source nodes to 2500 closest ones to the examined target node.

    (b) Having identified the two nodes with the shortest path between them, the routing service API is used for identifying the entire route.

5. Steps 3 and 4 are repeated until a single component remains.

The aim of this strategy is to improve connectivity to parts of the network that are close to points of interest. Appendix IV shows the components separated from the current network, with the gaps in the current network identified by this strategy shown in appendices V and VIII. Figure 8 shows the gaps in the planned network from this approach. As the aim of this strategy was to find gaps which would make the current network more cohesive, it is understandable that the emphasised gaps were not in the city centre, as was the case for the other two strategies.

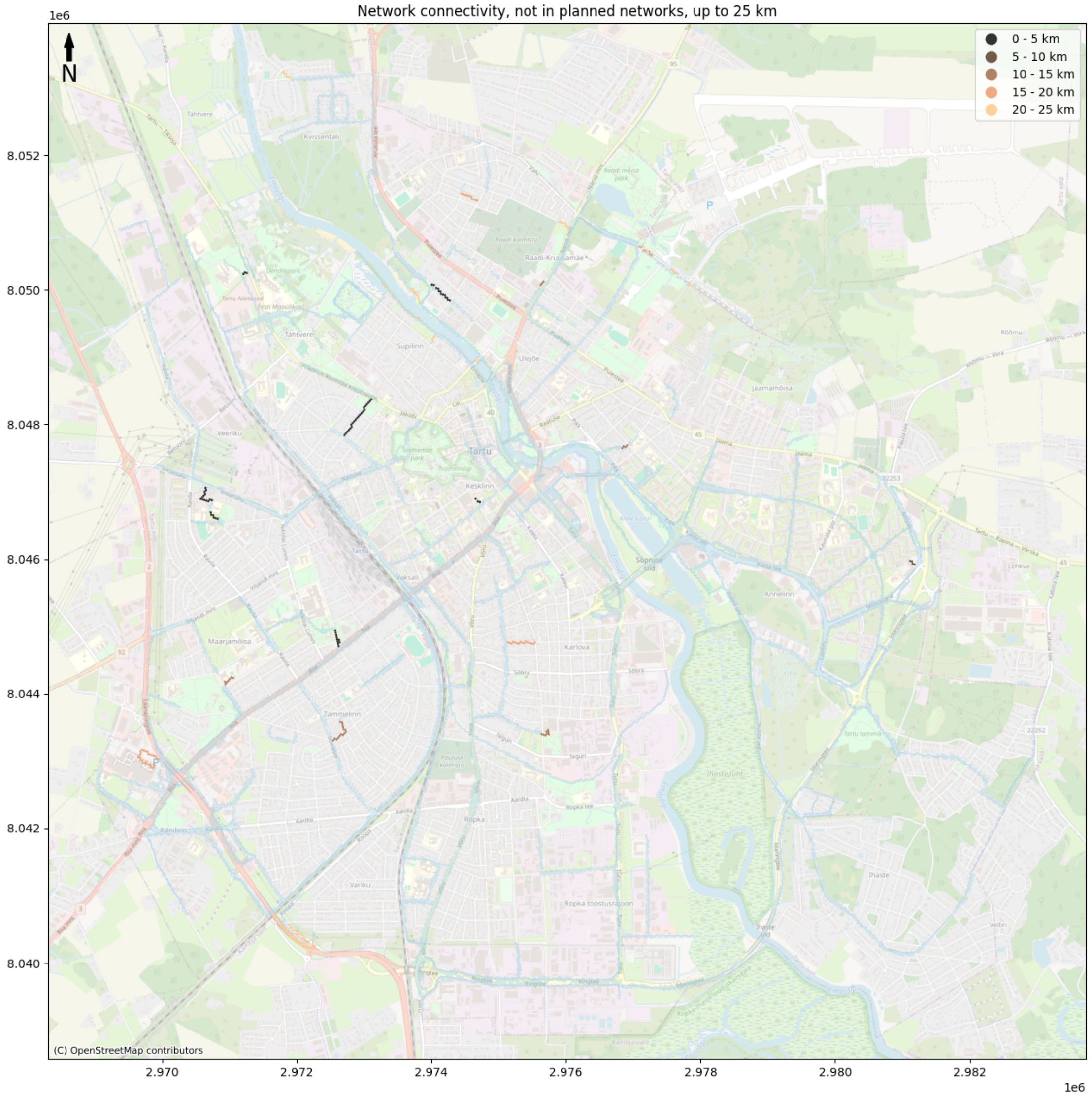


Figure 8. Comparison of the paths proposed by the strategy of improving network connectivity, excluding paths in planned networks

4.5 Combined strategy

The three strategies emphasise different aspects of the network - the routes used most by cyclists, the most direct routes to connect network stations, and improving connectivity of the network focusing on areas with the most potential points of interest to the cyclist. Since the proposed routes from these strategies varied in some cases, a combined strategy is proposed by using a multicriteria decision analysis (MCDA) approach. Previous research for cycling network expansion using MCDA has included using different score functions [BHR+17] [LPEG13] [Vyb21] to maximise the benefit of the users and minimise constraints.

Since previously used methodologies varied case-by-case, this thesis uses a MULTIMOORA model, which utilises different methods to compensate for weaknesses and biases from a single model. The model ranked the cells in the network by four factors:

1. **The number of actual trips** across the cell, derived from evaluating the current demand.
2. **The number of predicted trips**, derived from evaluating the predicted demand.
3. **Proximity to points of interest**, within a radius of 10 cells, which is equivalent to around 250 m. This parameter was chosen to emphasise routes that can connect the current network to buildings significant for the cyclists.
4. **Population in the proximity of the cell**, within a radius of 4 cells, which is equivalent to around 100 m. This was chosen as an additional criterion to improve connectivity for areas with a high population density. The population is visualised in appendix IX.

MULTIMOORA is a ranking system, which uses an aggregated result of three methods - Ratio System, Reference Point Approach, and Full Multiplicative Form [HHLH19]. As each separate method suffers from weaknesses, the combination attempts to overcome them. Since all criteria are to be maximised and the model is chosen to be used unweighted, the MULTIMOORA model is used in simplified form. Prior to applying the first method, the values of factors used in the model are normalised.

The Ratio System method aggregates the normalised factors and is a compensatory model, which means that a cell with low values in one factor and high values in another would rank similarly to a cell with medium values in both. The Reference Point Approach as a non-compensatory model finds the ranking of the cells based on their worst factor, choosing the highest value of all cells for each criterion as a reference point to be maximised. The Full Multiplicative Form uses the product of the normalised ratings of the factors to be maximised to produce the final rankings of the cells.

As a final step, the ranked cells were combined into proposed routes in the steps described in section 4.2. The resulting gaps identified from the combined strategy are discussed in section 5.1, and are visualised in figure 9, which shows the top 100 highest priority paths. The visualisation shows that the highest priority paths from the combination of strategies are concentrated in four regions - between residential buildings near Mõisavahe and Veeriku, in the old town streets around Rüütli, and residential area near Vaksali. This shows a deviation from the first two strategies, which identified more paths near the city centre.

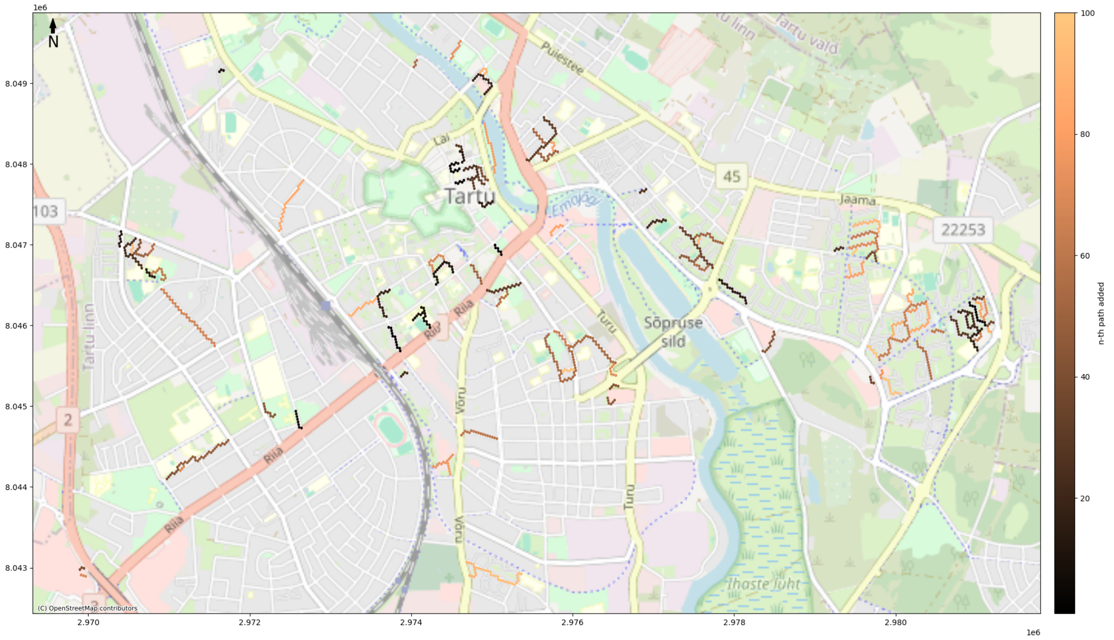


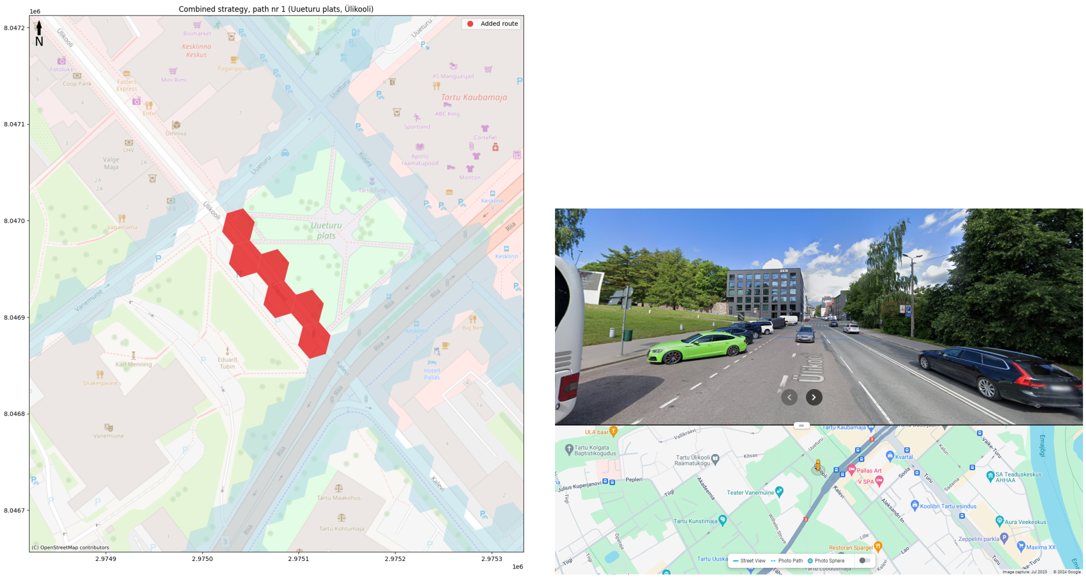
Figure 9. Comparison of the paths proposed by the combined strategy, excluding paths in planned networks

5 Discussion

5.1 Significant gaps in the planned cycling networks

Comparing the identified high priority paths to the planned main and auxiliary networks, the planned road sections cover most of the gaps identified by the combination of strategies. However, some paths are unaccounted for, of which the four highest priority paths identified by the MULTIMOORA model are examined and verified in this section. The verification is done based on the latest Google Street View screenshots.

The highest priority path identified by the model is displayed in figure 10. The gap on Ülikooli street between Vanemuise and Riia street has had an average of 1674 monthly trips, 2605 predicted monthly trips and is nearby many points of interest. Despite the low population in the proximity, the gap has a high cycling usage frequency and could benefit from a bike path.

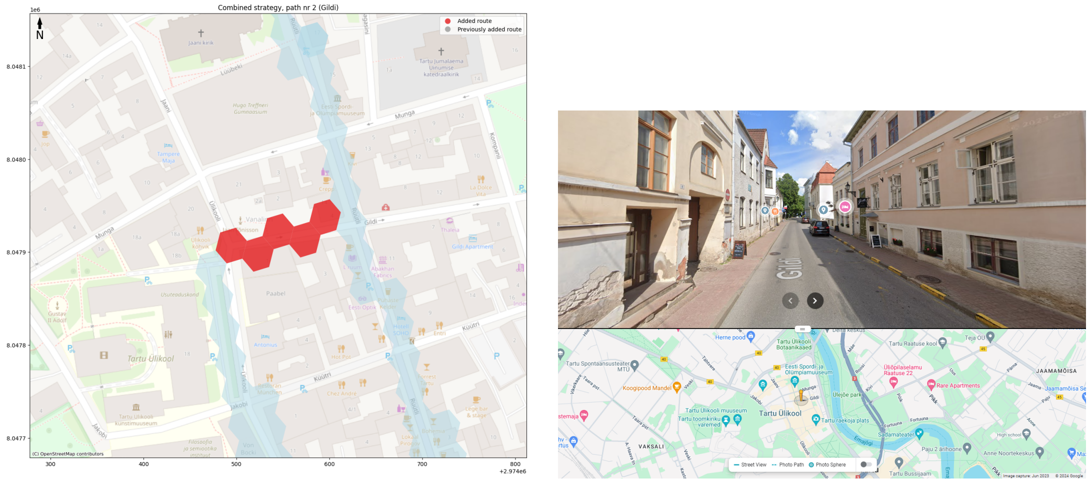


(a) Gap identified by the combined strategy

(b) Verification, Google Street View

Figure 10. First gap identified by the combined strategy

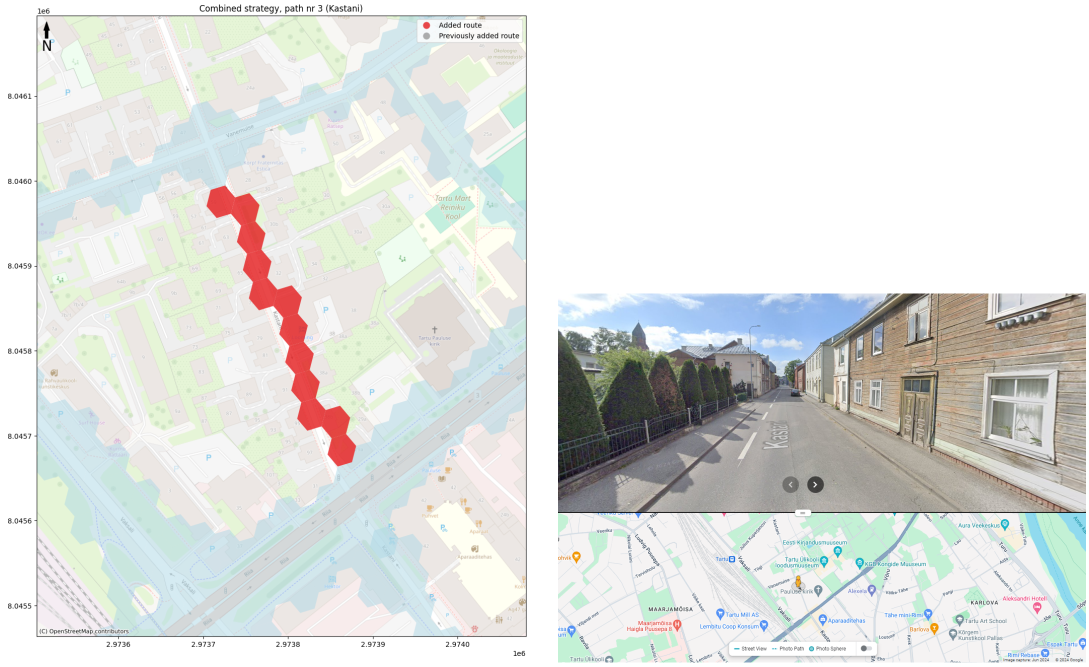
The second identified gap, displayed in figure 11, is on Gildi street, connecting Rüütli and Ülikooli streets. The gap has a lower usage frequency with average monthly trips of 445 of actual and 300 predicted, but connects a higher nearby population of 79. One significant issue with a bike path here would be the width of the road, since the verification image shows it to be a one-way street for vehicles with little room for pedestrians, so if a bike path should be built there, it would have to be on account of the parking spaces.



(a) Gap identified by the combined strategy (b) Verification, Google Street View

Figure 11. Second gap identified by the combined strategy

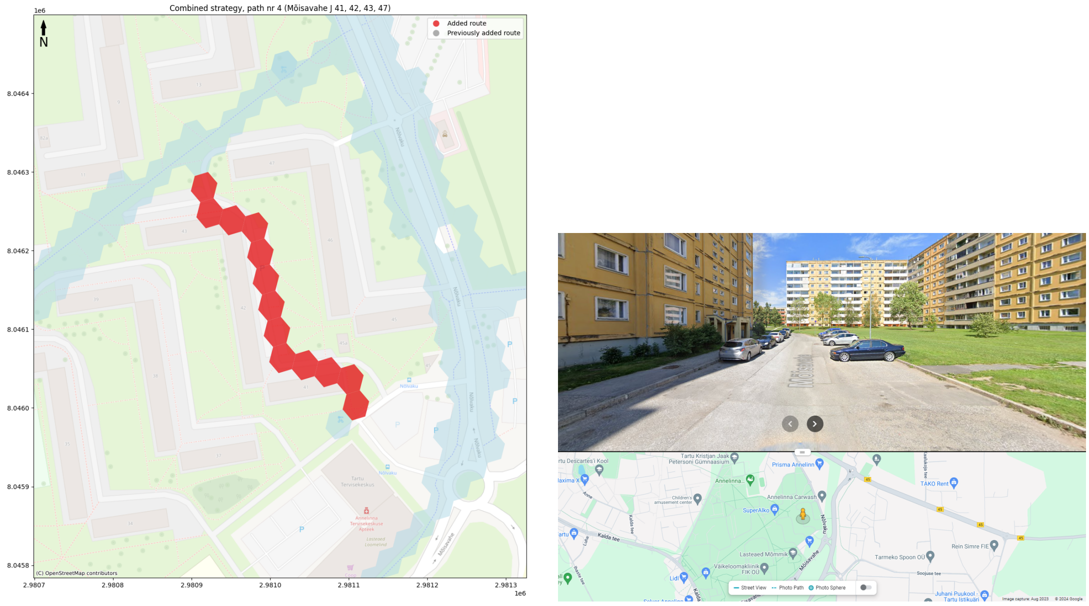
The third highest priority gap, in figure 12, is on Kastani street, connecting streets of Riia and Vanemuise. The gap has a monthly average of 278 actual and 705 predicted trips, with a nearby population of 705 and 1 point of interest (Mart Reiniku school building). Despite not being included in the plans of the main or auxiliary cycling networks, the verification image from June 2024 shows that a one-way cycling path has already been marked on this road, which gives more confidence in the results of the model.



(a) Gap identified by the combined strategy (b) Verification, Google Street View

Figure 12. Third gap identified by the combined strategy

The fourth gap, displayed in figure 13, shows a gap on Mõisavahe street between residential buildings. This is significantly different from the previously identified gaps in two aspects - an existing bike path is connected to a bike station instead of another path, and the main factor affecting it is not in bike trips, which total 250 and 41 monthly trips respectively for actual and predicted, but rather the population it connects, with a higher than average population of 479 in proximity.



(a) Gap identified by the combined strategy

(b) Verification, Google Street View

Figure 13. Fourth gap identified by the combined strategy

5.2 Prioritisation of planned paths from first three strategies

While the combined strategy brought out gaps in the planned networks, some planned paths should be emphasised for prioritisation. All of the proposed paths from the first three strategies, visualised in appendices VI, VII, and VIII, prioritise adding a cycling lane from the current network to a bike station not connected to the current network, on the streets of Jakobi, Põhja pst, Sepa, N. Lunini, and Elva. These paths would be useful in improving the accessibility of the bike sharing system, providing the commuters convenient access to and from the bike station.

Two of the proposed paths would also add the connection from between different parts of the network. The path at Jakobi street would connect the bike path on K. E. von Baeri street to the J. Hurda bike station, as well as connect to the network at F. R. Kreutzwaldi street. Since the method for finding the paths between the nodes in the network focused only on the shortest path, the proposed path shows a connection only to the bike station. The final proposed path connects two different parts of the network between the intersection of Näituse-Puusepa-Veeriku-Ilmatsalu-Vitamiini, and the cycling and pedestrian path between Ravila-Lunini-Puusepa.

The first most significant gap in the current network was identified to be on Jakobi street, connecting the bike path on K. E. von Baeri street to the J. Hurda bike station, as well as connect to the network at F. R. Kreutzwaldi street, as shown in figure 14. Since the method for finding the paths between the nodes in the network focused only on the shortest path, the proposed path shows a connection only to the bike station. This path is planned to be added to the auxiliary cycling network. However, considering a monthly average of 777 actual and 1133 predicted bike trips, its importance in the network as a whole should not be understated.

Figure 14. Planned path on Jakobi street

The ordinary cyclist might not use the path to go from K.E. von Baeri street to Jakobi street, since the first path goes downhill, and the second uphill, and cyclists generally prioritise avoiding elevation changes. However, this path is significant in connecting the established bikeway on F. R. Kreutzwaldi street to significant points of interest nearby in Kesklinn, e.g. the main building of the University of Tartu, and Tartu Kesklinna Kool. As visible from the visual confirmation in figure 14 from Google Street View, cyclists on this section of the road have to share the narrow road with cars, creating potentially dangerous situations.

The second gap, illustrated in figure 15, connects the network at the intersection of Sõpruse pst and Jaama street to the bike station at Põhja pst. The section of the road has no separation for cyclists, but is near multiple points of interest, lies in the middle of a residential area, and has a monthly average of 800 actual and 994 predicted trips, so it could benefit from safer access to cyclists. It is planned to be added to the main cycling network.

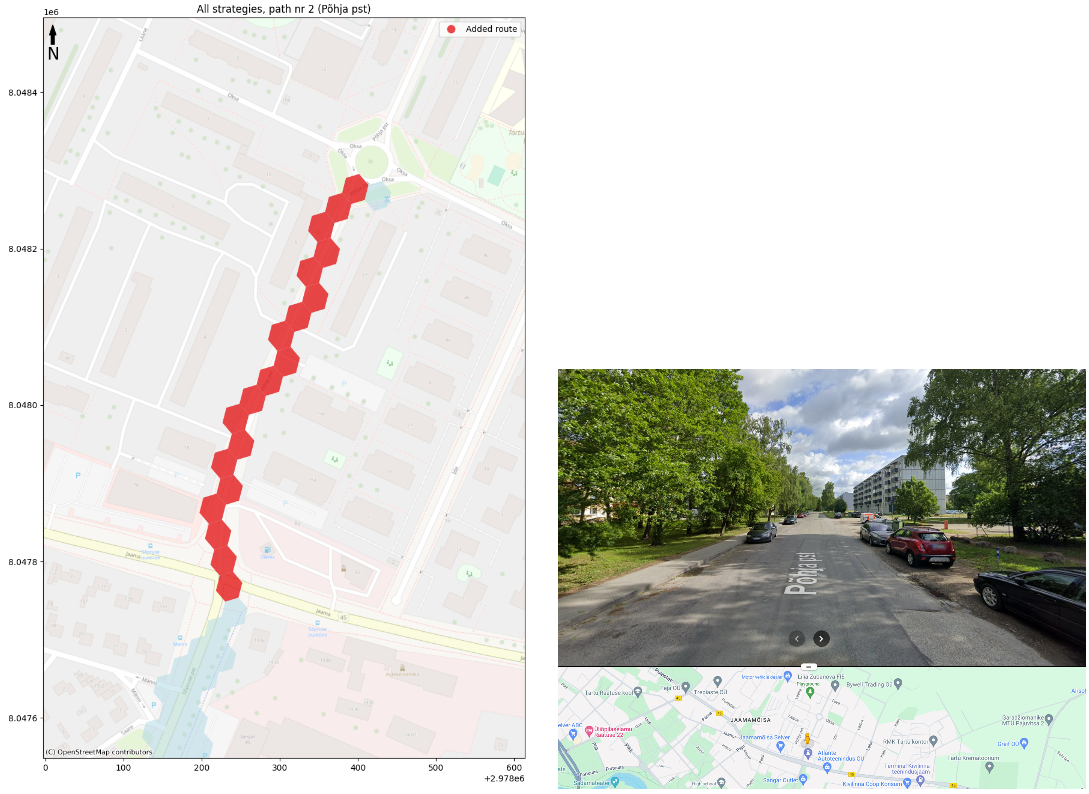


Figure 15. Planned path on Põhja pst

The third gap, shown in figure 16 connects the bike station on the intersection of Sepa and Jalaka, to Võru street. Currently cyclists are forced to use either the narrow pedestrian paths or the roadway, creating possibly dangerous situations. The path has had a monthly average of 611 trips, with 1339 predicted trips, and is planned to be added to the auxiliary cycling network.

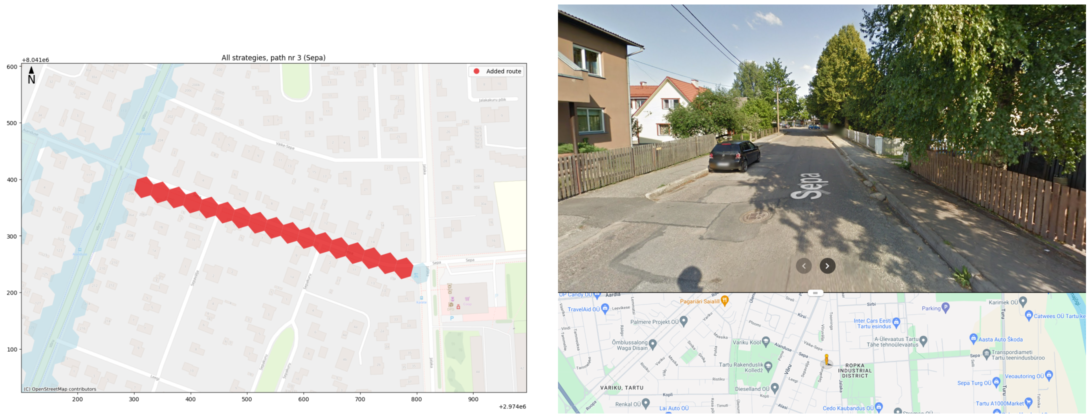


Figure 16. Planned path on Sepa street

The fourth gap was identified on N. Lunini street, connecting an intersection of N. Lunini, Veeriku, and Näituse to Nooruse street and Maarjamõisa hospital, as seen in figure 17. This long path is planned to be added as part of the main planned network, and has a higher than average monthly usage frequency with 645 actual and 796 predicted trips.

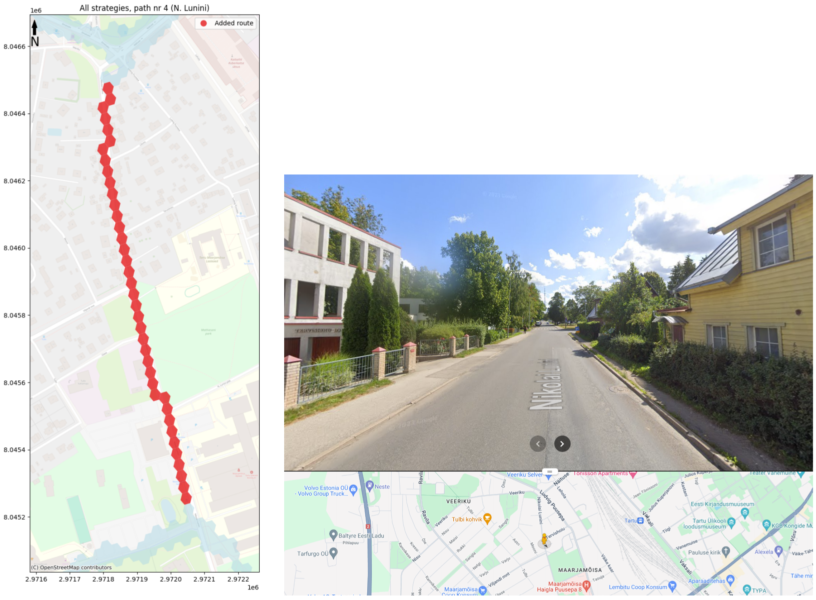


Figure 17. Planned path on N. Lunini street

The final gap in the current network, that is planned in the auxiliary network, connects the bike station next to Tamme stadium to Raudtee street, visualised in figure 18. While the path is short in a quiet neighbourhood, cyclists could benefit from separated movement to and from the bike station on the narrow street.

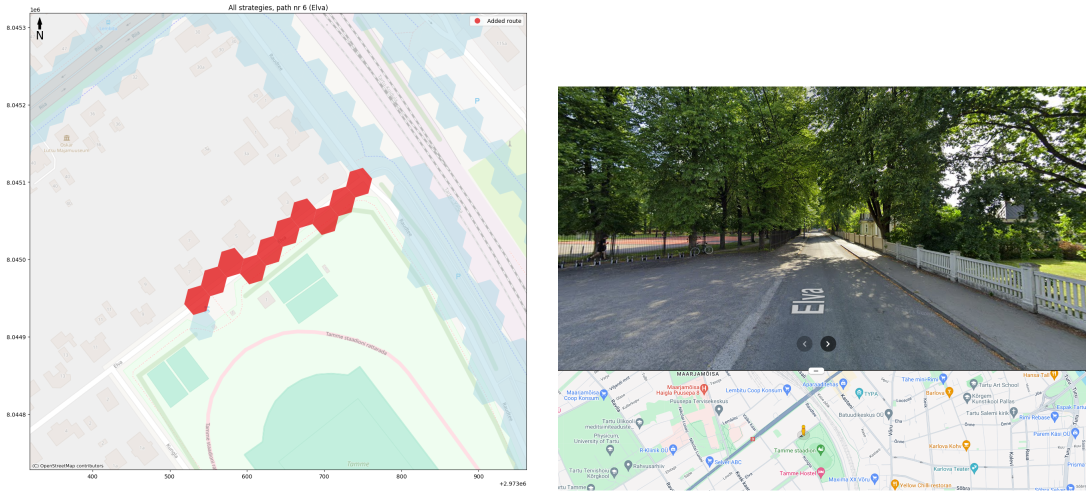


Figure 18. Planned path on Elva street

5.3 Cycling path prioritisation model evaluation

The three separate and one combined strategies aimed to include different goals to identify gaps in the cycling path networks, but some biases and unsuccessful approaches should be noted. The gaps in the planned cycling network were reviewed from four approaches, utilising different data sources and methodologies. While these various methods attempted to cover the needs of cyclists, they are not exhaustive.

The strategy to estimate the demand of cyclists included a selection bias in examining the trips between current bike stations. This approach excludes the needs of cyclists, who do not use the bike sharing system, which should be considered when making decisions based on this strategy.

The proposed models for prioritisation could benefit from the inclusion of the width of the roads for pedestrians and cars, to exclude proposed paths, which do not have sufficient width to add bike paths. This limitation was not included in the proposed models, since the data for the width of existing paths was incomplete. An additional limitation could be considered for current bike paths which are unidirectional, to find roads where cyclists could benefit from bidirectional paths. Future studies could improve the model with data from shared e-scooters, which are currently operated in Tartu only by Bolt. The combined strategy model could benefit from improvements by assigning weights to the four factors used based on the priorities of city planners.

Some approaches, which were experimented with, did not work out, but might be useful for further studies. H3 map matching was initially used with a resolution of 11 (average hexagon small diameter of 122 meters), which resulted in the exclusion of shorter suggested routes. On the other hand, a resolution of 13 (average small diameter 17 meters) turned out to be computationally inefficient for network analysis tasks.

6 Conclusion

Cycling infrastructure planning has recently seen an increase in using micromobility location data for a more comprehensive evaluation of the users' movement patterns. To increase the share of cyclists in Tartu, it is necessary to make data-driven decisions with respect to expanding the infrastructure that cyclists depend on. Tartu has an expansive cycling network, with plans for its expansion in the next three or more years, which adds important paths to improve connectivity across the city.

The objective of this thesis was to identify gaps in the current, as well as planned, cycling networks of Tartu, and provide input for new paths from network expansion prioritisation strategies. The four strategies employed for detecting the gaps and their prioritisation revealed road sections in different parts of the city, with Kesklinn prioritised the most for strategies, that evaluated the Tartu Smart Bike data, and districts at the edge of Tartu for the strategy of improving network connectivity.

The four strategies focused on different aspects of the network. The current demand of the cyclists in Tartu was evaluated by map matching the GPS data of the Tartu Smart Bike users to H3 hexagons for a standardised approach to combining data from different sources. The optimal demand of bike share users was predicted from the origin-destination matrices by evaluating the most direct walkable paths. Connectivity of the current network was examined by connecting the network components with the most points of interest connected to them. The strategies were combined with an additional parameter of considering the nearby population.

The findings from this thesis offer insights into the patterns of current Tartu Smart Bike users, and estimate the benefits from new strategies for expansion of the network. Future studies could focus on improving the prioritisation model by examining the usage patterns of other users of cycling paths, including users of regular bikes as well as e-scooters. Another approach to gap verification would be to use image recognition from Google Street View to automate the validation process, and possibly include additional information on the bike paths to consideration.

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Appendices

I. Points of interest

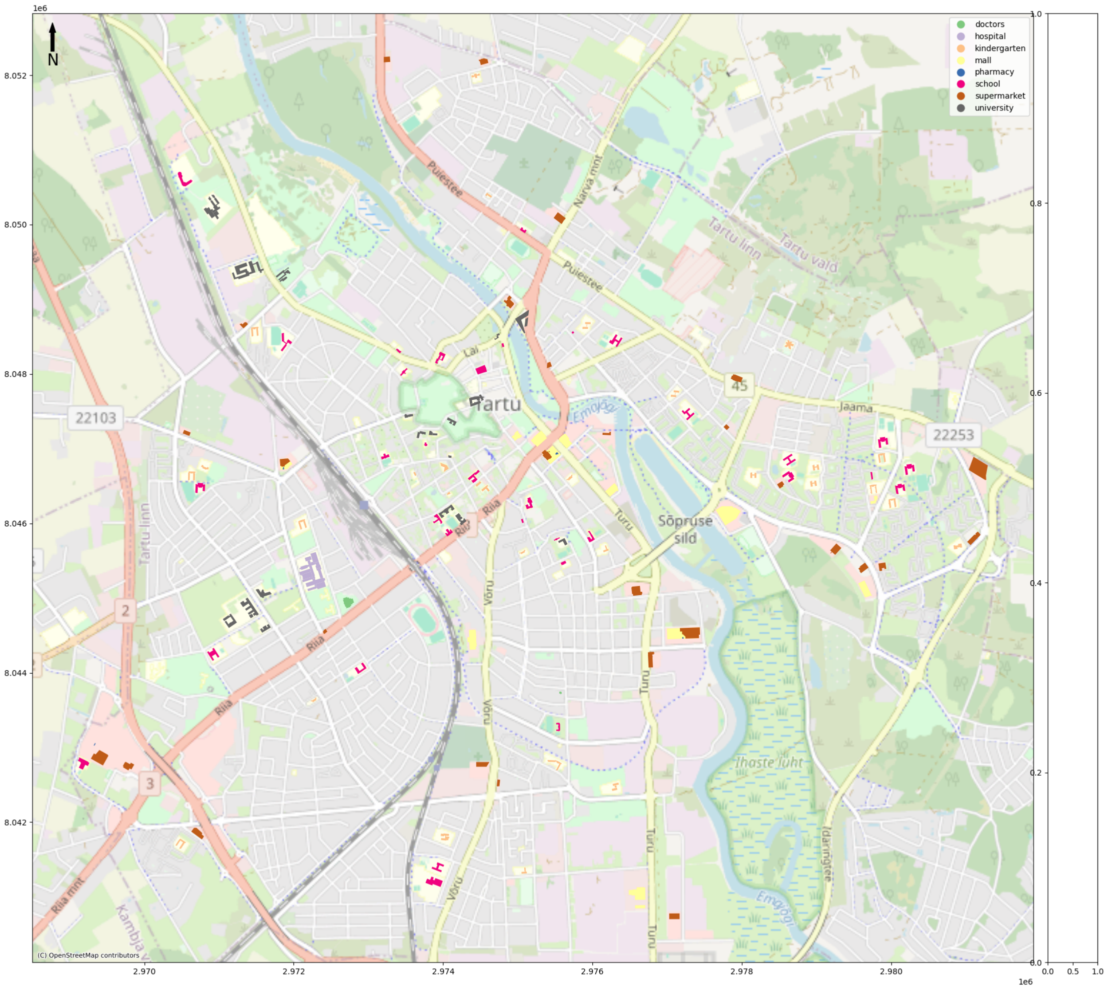

Figure 19. Points of interest

II. Proposed paths from examining current cycling demand

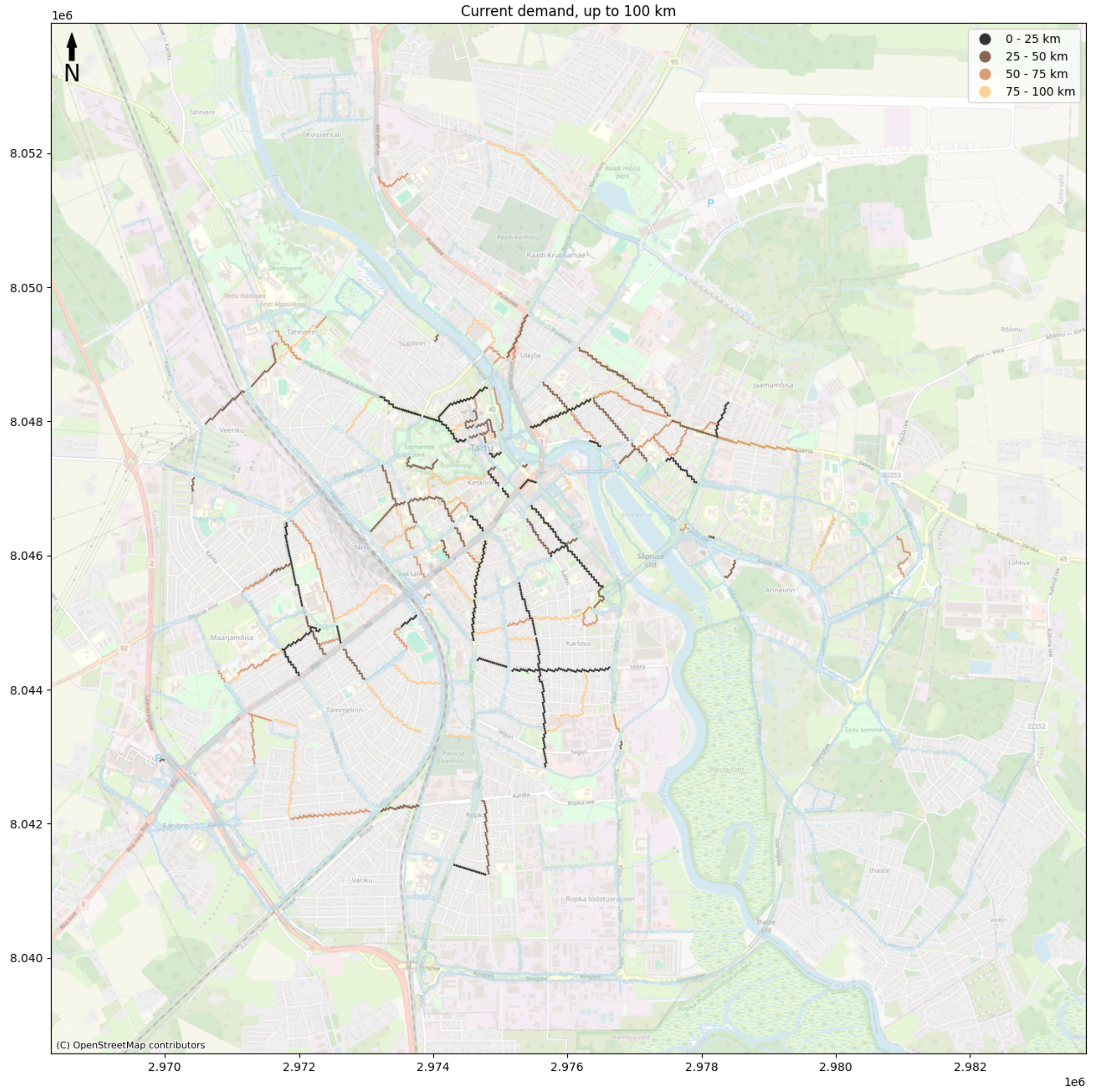

Figure 20. Overview of the gaps in the current network up to 100 km, identified by evaluating the current demand

III. Proposed paths from estimating potential demand

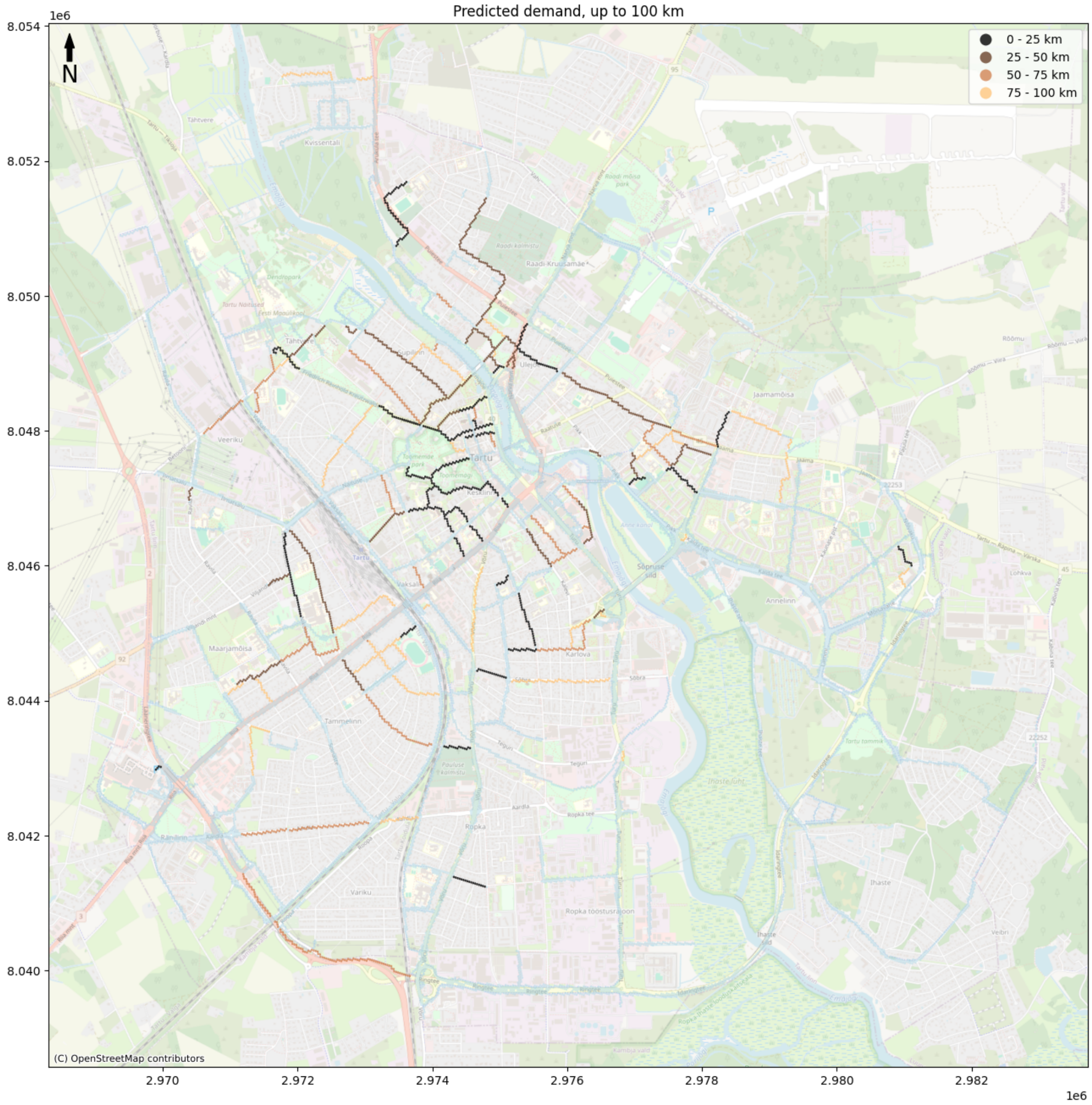

Figure 21. Overview of the gaps in the current network up to 100 km, identified by estimating potential demand

IV. Current network components

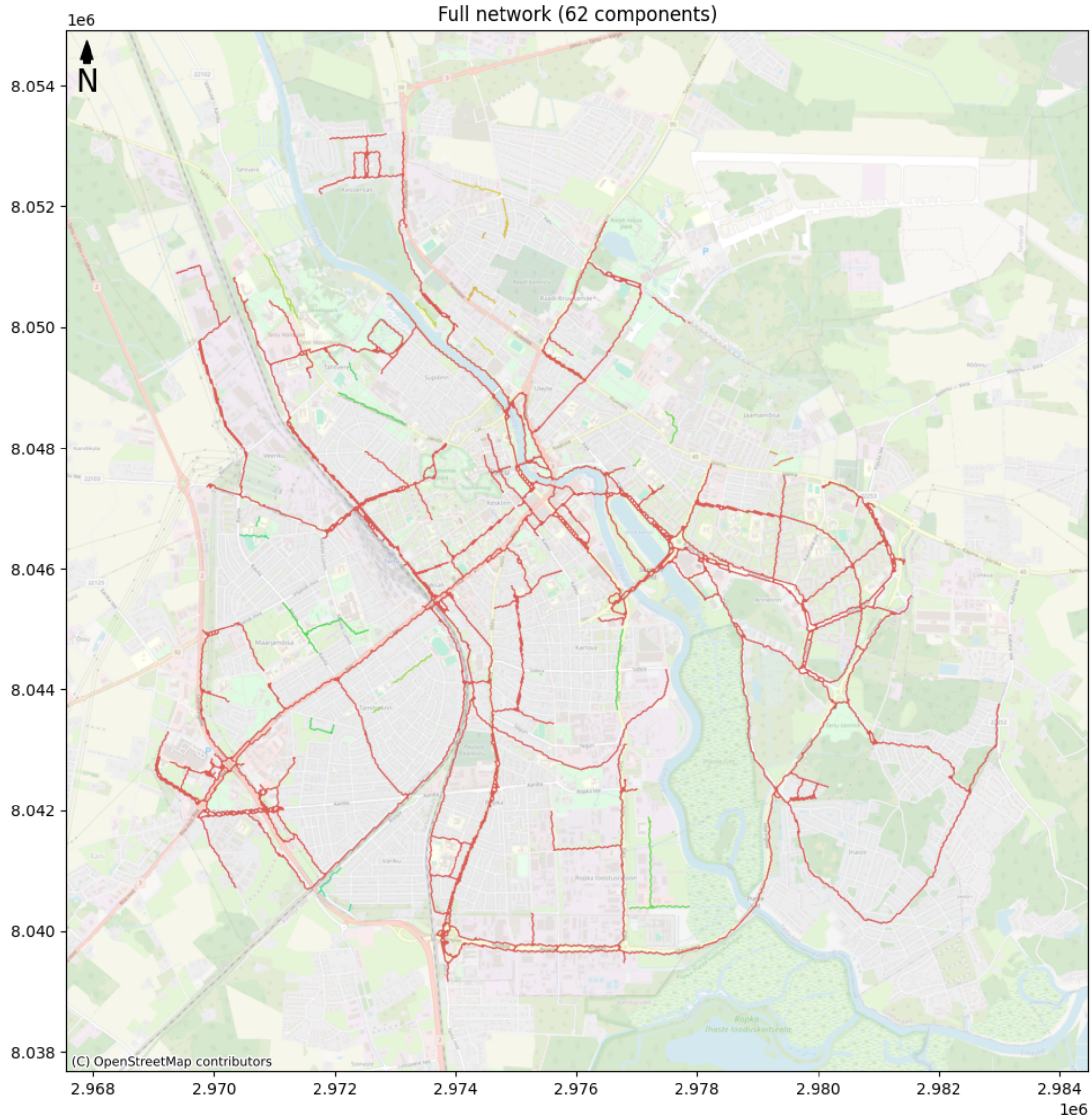

Figure 22. Current network components

V. Proposed paths from examining the network connectivity

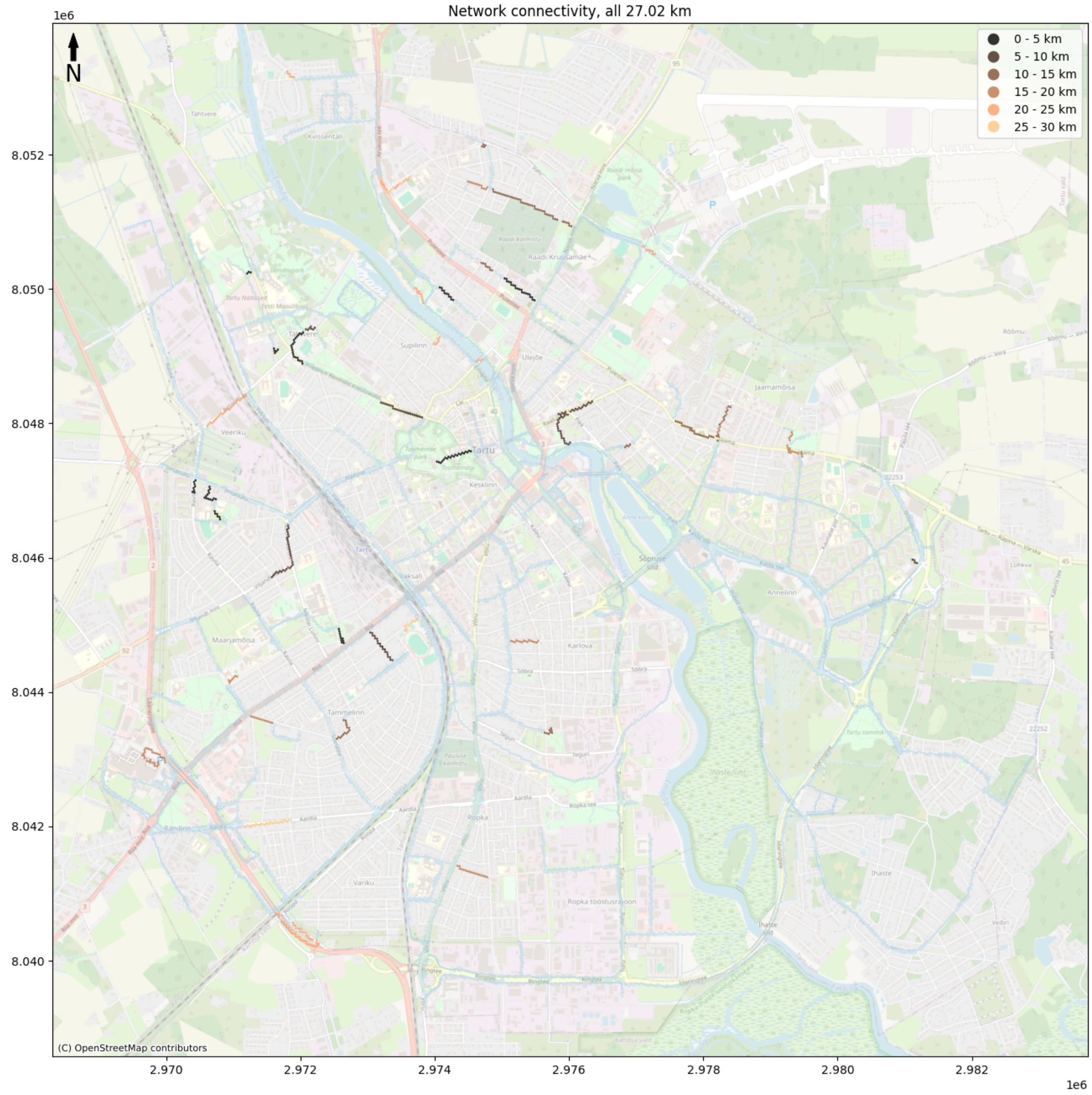

Figure 23. Overview of the gaps in the current network up to 100 km, identified by evaluating the current demand

VI. Most significant gaps from evaluating current demand

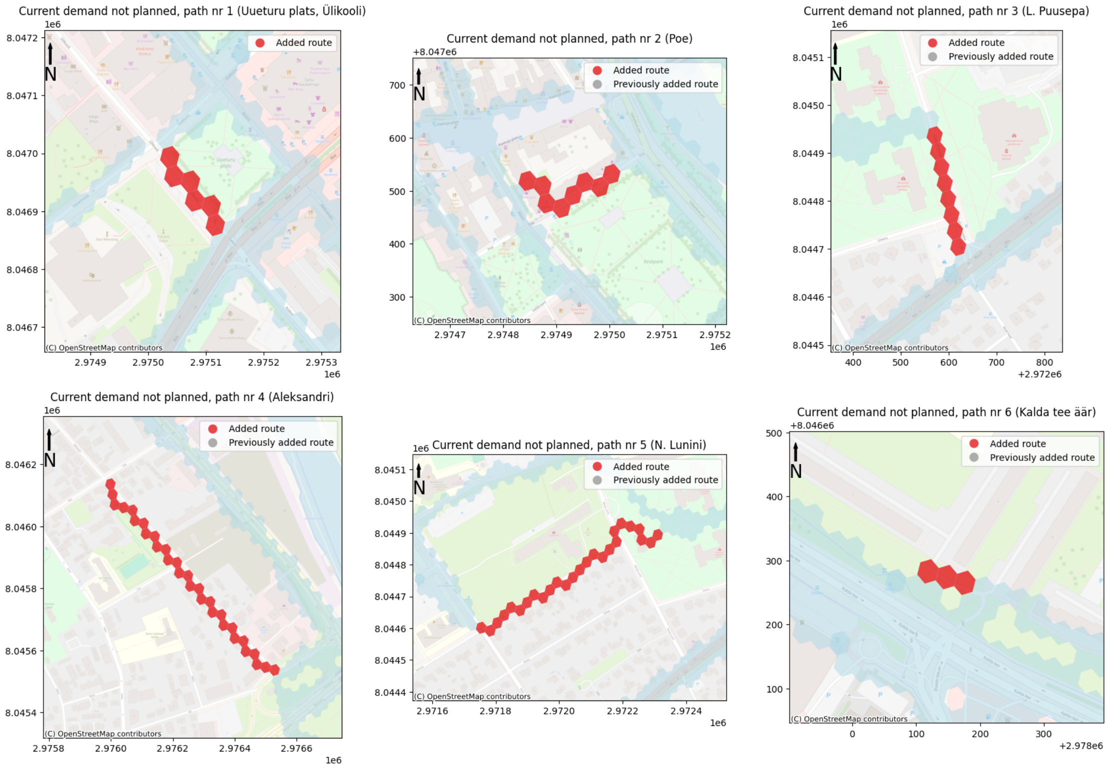

Figure 24. Most significant gaps identified by evaluating current demand

VII. Most significant gaps from estimating potential demand

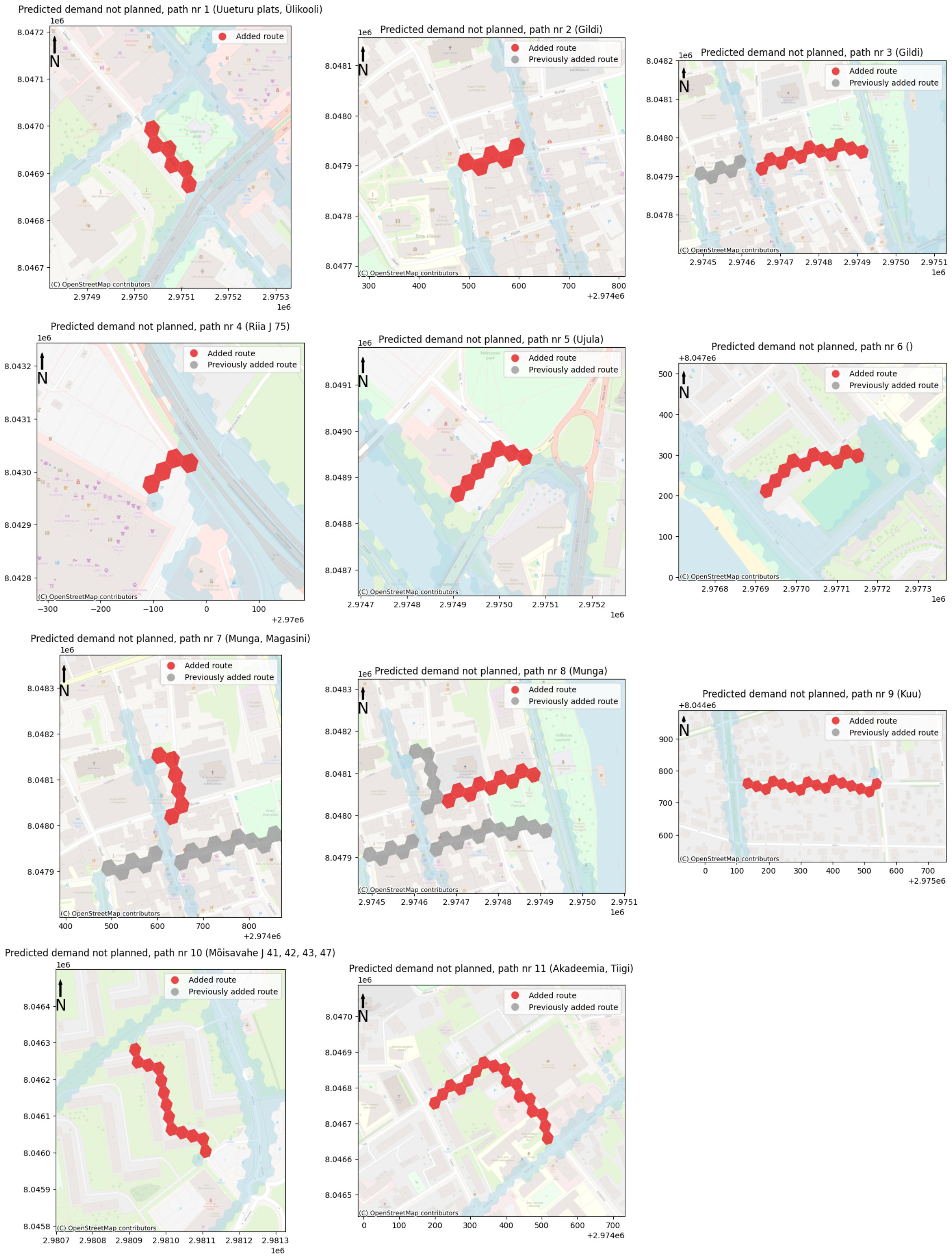

Figure 25. Most significant gaps identified by estimating potential demand

VIII. Most significant gaps from improving network connectivity

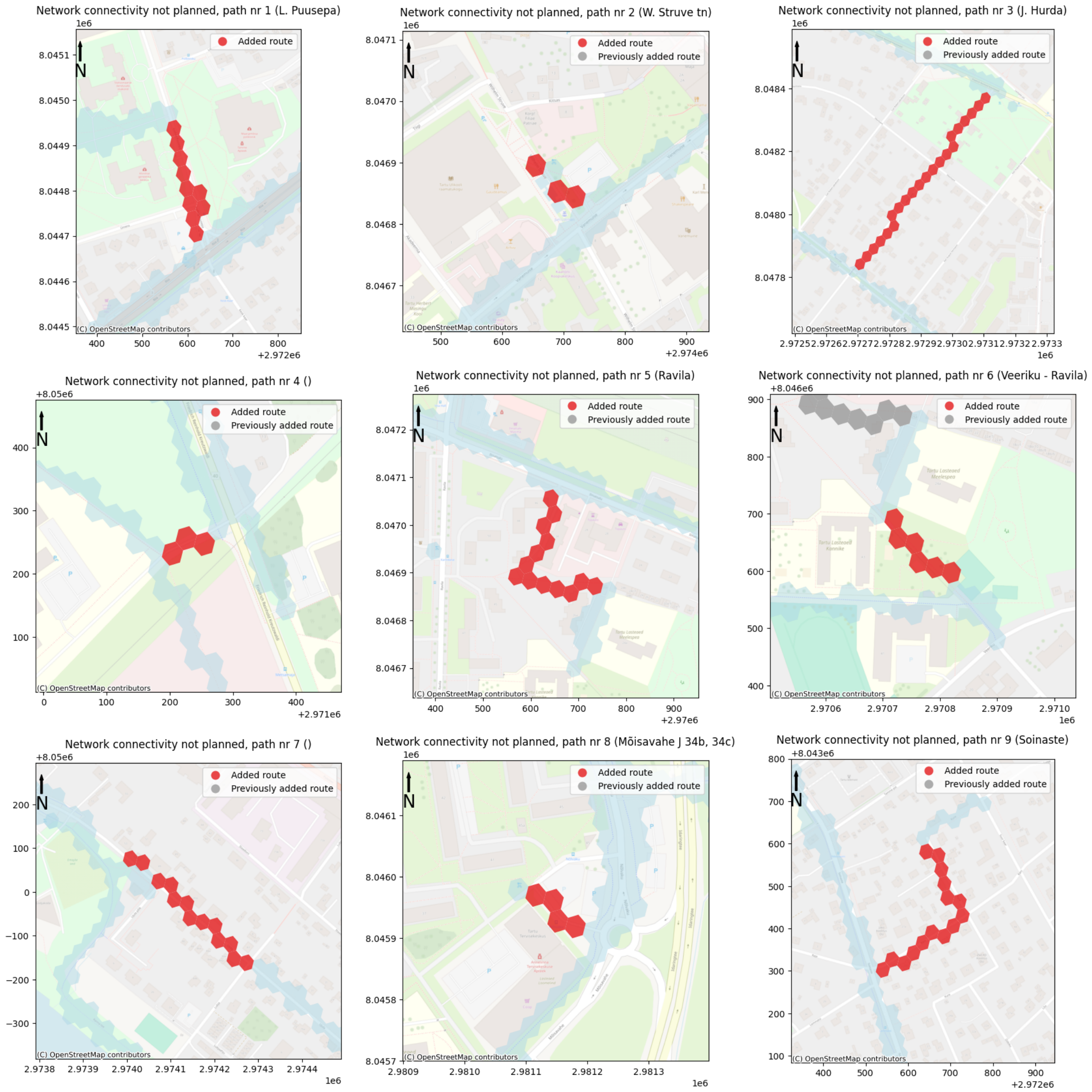

Figure 26. Most significant gaps identified by improving network connectivity

IX. Population grid of Tartu

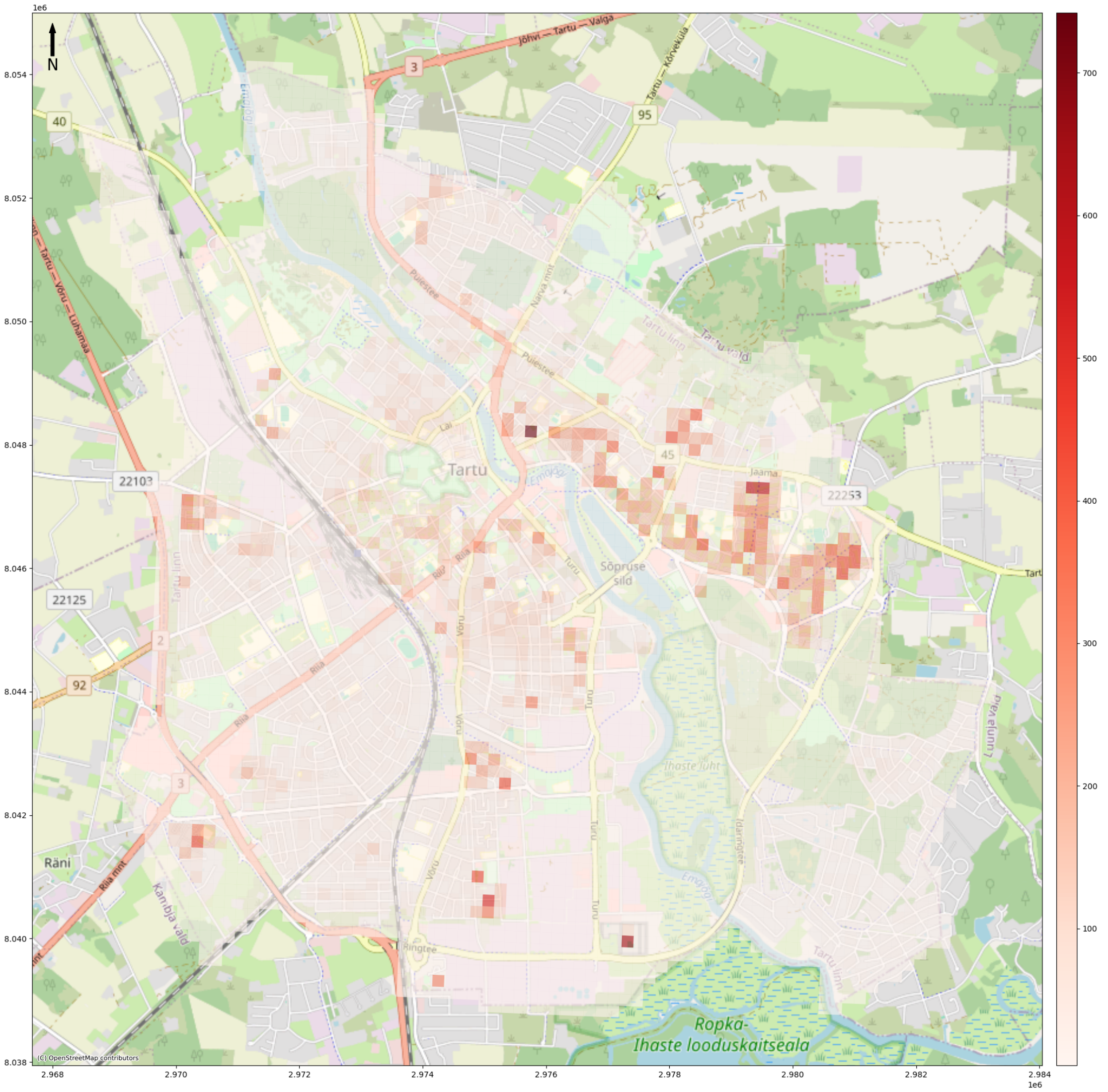

Figure 27. Population grid of Tartu

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