



Visualizing the Influence of New Public Transport Infrastructure on Travel Times

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Abstract

Due to the global climate change and increasing traffic volumes in cities, a shift from individual to public and multimodal transport is aspired. Travel time is one of the most important aspects for many people when choosing their mode of transportation. This leads to the requirement that changes in travel times have to be considered when planning new public transport infrastructure. This research paper presents and compares different techniques for visualizing the impact of new lines in existing public transport networks on travel times. The general approach of simulating timetable data and calculating intermodal travel times considering public transport and walking is being applied to two current infrastructure projects in the city of Bonn and the surrounding region. The created maps generally aim to visualize the spread in travel times between existing and extended transportation networks discretized by different spatial units such as rectangles or postal code areas. In comparison to other common methods which typically require two maps for two different scenarios (e.g. in case of isochrones), our approach gives the opportunity to combine all relevant information within one map. It is also shown how to apply bivariate choropleth maps for displaying travel times and how to visualize improvements in the accessibility of multiple target points of interest at once.

Keywords Maps · GTFS · Planning · Traffic · Grid · Projection · Isochrones

Visualisierung des Einflusses neuer öffentlicher Verkehrsinfrastruktur auf Reisezeiten

Zusammenfassung

Aufgrund des globalen Klimawandels und des zunehmenden Verkehrsaufkommens in Großstädten, wird eine Verlagerung vom motorisierten Individualverkehr hin zum öffentlichen Personenverkehr angestrebt. Reisezeiten gehören für viele Menschen zu den wichtigsten Aspekten bei der Wahl des verwendeten Verkehrsmittels. Daraus ergibt sich die Schlussfolgerung, dass Änderungen von Reisezeiten bei der Planung neuer öffentlicher Verkehrsinfrastruktur berücksichtigt werden müssen. In diesem Artikel werden verschiedene Techniken zur Visualisierung der Auswirkungen neuer Linien in bestehenden ÖPNV-Netzen auf Reisezeiten vorgestellt und miteinander verglichen. Der grundlegende Ansatz, intermodale Reisezeiten basierend auf simulierten Fahrplandaten zu berechnen, wird auf zwei aktuelle Infrastrukturprojekte in der Stadt Bonn und der umliegenden Region angewendet. Die erstellten Karten zielen darauf ab, Unterschiede in den Reisezeiten zwischen bestehenden und erweiterten Verkehrsnetzen zu visualisieren. Dabei werden für die Darstellung vorwiegend Rasterkarten mit räumlicher Diskretisierung basierend auf tatsächlichen Grenzen wie Postleitzahlgebieten sowie auf künstlichen Geometrien

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verwendet. Im Vergleich zu anderen gängigen Methoden, die typischerweise zwei Karten für zwei verschiedene Szenarien erfordern (z.B. im Fall von Isochronen), bietet unser Ansatz die Möglichkeit, alle relevanten Informationen in einer Karte zu kombinieren. Es wird auch gezeigt, wie bivariate Choroplethenkarten zur Darstellung von Reisezeiten eingesetzt werden können und wie veränderte Erreichbarkeiten mehrerer Zielpunkte gemeinsam in einer Karte visualisiert werden können.

1 Introduction

In times of global climate change and increasing traffic volumes in cities, the demand for a well-functioning public transport system is increasing. This research paper aims at visualizing the impact of new public transport infrastructure on travel times as a contribution to mobility planning. Therefore, different visualization approaches are being discussed, implemented and evaluated through the example of current infrastructure projects.

The model region for practical examples in this article is the city of Bonn and its surrounding municipalities. In comparison to other German cities, the use of public transport in Bonn is already higher than average (Nobis et al. 2020). Since there are still weaknesses in parts of the network and the overall demand is increasing, there are several ongoing infrastructure projects in the region. One example in this article is an urban ropeway between Bonn-Ramersdorf in the valley of the river Rhine and the large medical center on the hill Venusberg which is in discussion. Another one which is already under construction is the extension of the tram line S13 connecting Bonn-Oberkassel and the nearby town Troisdorf.

A typical issue during the planning of new infrastructure is that the planners' view is focussed on the planned project but does not have a look on the variety of multimodal trips that is done by the users in the end (Brand et al. 2017). From the users' perspective, the total travel time of a trip also includes waiting times and the last mile to the destination. Frank et al. (2008) state that accessibility, respectively, travel times, are among the most influential factors regarding the perception on competitiveness of transport devices. Expansion of public transport usage therefore results from reduced travel times. Hence, one of the main goals of this article is to elaborate visualization approaches for travel time data and compare them regarding their eligibility for planning and public communication. Therefore, the first important step is to work out visualization techniques that are capable of illustrating travel times in road and rail networks.

Another important aspect is the comparison between maps, especially before and after the implementation of new infrastructure. Therefore, the integration of simulated data and techniques for comparing two maps will be discussed and executed on the example of the two mentioned infrastructure projects in Bonn. Considering the fact that travel times using timetable-based intermodal transport

are dynamically changing dependent on the starting time, a method for calculating averaged travel times will be introduced.

A user study is being conducted to evaluate the elaborated visualization and map comparison techniques for analyzing the effect of new public transport infrastructure on travel times. Goal of this study is to find out if the visualization approaches fulfill their purpose and which is the most suitable one in the present application. Also, it is aspired to compare the eligibility of different maps for user groups with and without previous knowledge on cartography by asking for possible issues in reading and understanding the maps.

2 Related Work

A common goal of geoinformation and cartography is to translate the real world's complexity into simplified reproductions to be easily understood by a large bandwidth of different user groups (Knight 2004). In most cases, an appropriate and approved way to represent spatial information are two-dimensional maps which nowadays are created and also used predominantly in digital form. To create an effective map, it is crucial to clearly define its goals, match it to its user group and use suitable data. Most of the commonly used software is layer-based and can correlate data from different sources by stacking several layers on a background map (Lobo et al. 2015).

In this article, the goal is to make travel times and changes in travel times easily perceivable in maps by integrating timetable data of new infrastructure in the calculation of travel times. Since maps are tools for visual communication that use the user's spatial cognition (Tversky 2000), a background map of the affected area's road and public transport network is suitable for a good orientation. While details like small dead-end streets and single buildings do not play a major role here, it is important to accentuate the most important roads, stations and natural borders like rivers in order to ensure a good orientation and correct spatial assignment of visualized travel times in the map. Nonetheless, we set the main focus on the displayed travel times.

2.1 Algorithmic Approaches and Data

A road network is typically represented as a graph structure to handle it in computer applications with crossings as nodes and roads as edges. For finding the shortest connection

between two nodes in a graph, Dijkstra's algorithm (Dijkstra et al. 1959) is a common approach. The algorithm solves a single-source search problem starting from one node in the graph and can be terminated when the target node is reached and the routing task is fulfilled. An important extension of Dijkstra's algorithm including a goal-directed heuristic is the A-star algorithm (Hart et al. 1968). Both of these classical approaches are applicable for graphs. Thus, for timetable-based public transport connections, the timetable information has to be transformed into a graph representation. Finding shortest connections in public transport networks is an important task for mobile applications to guide users on their way and therefore plenty of free and open source software for this task has emerged during the last years. An approach for routing tasks in public transport networks was presented by Pyrga et al. (2008) with the so-called time-expanded model. The authors transform the timetable-based public transport network into a graph structure, introducing arrival, transfer and departure nodes for each station and edges between the nodes. A schematic example for a sample station is shown in Fig. 1. The graph structure allows shortest path algorithms to find the fastest connection from one station to another using public transport lines.

Common ground of most modern tools for public transport routing is the use of the General Transport Feed Specification (GTFS) format that was introduced by Google (2006) to permit easily usable and exchangeable timetable data for public transport service applications. Since good data quality is the basis for good maps (Kamw et al. 2019), there is a large dependency on the transport companies that create and publish GTFS data.

GTFS-based open source software for the computation of shortest connections using combinations of public transport and walking was among others published by Forsch et al. (2021) and the OpenTripPlanner project (Bast et al. (2010); Morgan et al. (2019); Young (2018)). Both are Java packages that require a GTFS dataset and Open Street Map (open data project for maps and spatial information) road data for the desired region and offer functions for finding fastest paths and travel times between given locations. These software packages are adequate mainly for researchers and GIS experts in transport companies. Since common users

typically do not have fast computers and the possibility to set up large software environments, an interactive web-based tool for accessibility visualization in public transport networks with server-client architecture was published by Schoedon et al. (2016).

Calculated travel times and connections can differ a lot depending on the given starting time and day because of the timetable-based public transport connections in GTFS datasets. This has to be kept in mind when analyzing generated data from the mentioned software, so that not every result is considered as universally valid.

2.2 Visualization of Routes and Accessibility Zones

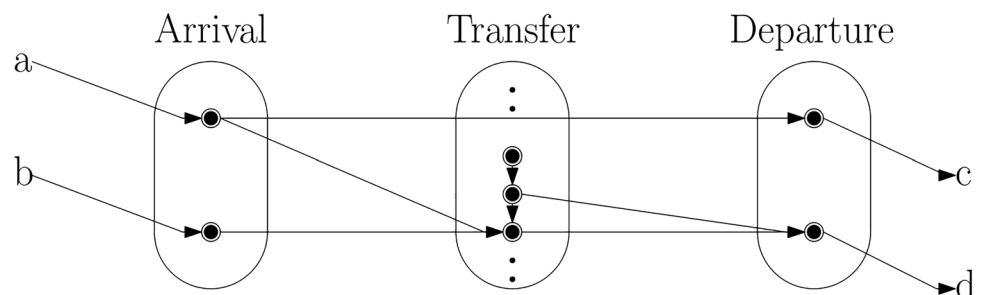
An important function of navigation systems is to compute and display a route between two points, including the distance and travel time. In the context of navigation and routing tasks, Gartner and Radoczky (2005) recommend a combination between topographic and schematic maps for good orientation. A reasonable weighting between abstraction and level of detail should be considered to guarantee the intended visibility of spatial information and orientation not only for the visualization of a single route.

Displaying a single route helps common users to get from A to B, but for receiving general information about travel times in an area it might not be the most functional approach. However, for analyzing local accessibility, it is interesting to compute travel times on one and the same route at different times to find out if there are large temporal differences. Therefore, start and/or end locations for the route should be chosen wisely from significant points of interest. According to Jaepinen et al. (2013), reasonable choices for points of interest can be major employment concentrations, shopping destinations, university campuses, recreational areas and tourist attractions.

Hansen (1959) explains accessibility as the capability of reaching destinations. To define a measure of accessibility, Liu and Zhu (2004) distinguish between five sets of parameters:

- Spatial unit: the basic unit area for which the accessibility is specified

Fig. 1 Time-expanded model for public transport routing at a sample station using the approach of Pyrga et al. (2008)



- Travel reasons, e.g. reaching the job or school
- Origins and destinations of trips
- Modes of transportation
- Travel impedance: distances, travel times, line changes

Since point-wise considerations do not give large amounts of visible information on accessibility, the definition of two-dimensional zones is beneficial. One could for example use the postal code zones to subdivide a city or federal state into spatial units. A possibility of calculating accessibility measures would then be to compute the shortest path from one general starting point to targets in the middle of each postal code zone.

A very common approach of visualizing accessibility zones is the use of isochrones. The term isochrone technically means line of identical time. Regarding accessibility, typically one isochrone covers all places on a map that are reachable within a given maximum travel time. The standard procedure therefore is to first compute the reachable parts of a given network that can be reached within a given time and then connect them to an area by a convex hull (smallest enclosing polygon) or other polygonal structures (Bolzoni et al. 2016). One specific approach for isochrones with the goal of a schematized visualization and low visual complexity was introduced by Forsch et al. (2021). Similar to the basic principle of most metro maps, the isochrones are based on octilinear polygons, which means that only eight pre-defined directions are used to shape the polygonal representation. Allen (2018) provides an alternative to areal isochrones which links travel times to network edges taking the structure of public transport or road networks in the foreground in visualizations.

2.3 Map Comparison

The field of map comparison is associated with a relatively high level of uncertainty and strongly depends on the applied technique which should be chosen with care for the particular application. The questions what aspects should be evaluated and how similarity is assessed lead to a comparison approach with the highest possible value for the case under consideration (Foody 2007). According to Visser and De Nijs (2006), reasons to compare maps are:

- Detecting temporal/spatial changes or hotspots
- Comparing different theoretical models, methodologies or scenarios
- Calibrating or validating landuse models
- Analyzing model uncertainty and sensitivity
- Assessing map accuracy

Depending on the available data, the appropriate techniques differ from intensity-based analysis methods which

are predominantly meaningful for orthophotos (maps created from aerial photography) (Lilienthal et al. 2007) over methods with a distance weighted moving window considering spatial structure and overlap in raster maps (Hagen-Zanker 2006) to special techniques for road networks using path-based distance measures between geometric graphs (Ahmed et al. 2015). Simple pixel-by-pixel approaches are still useful for many purposes but often fail to reveal important similarities and differences (White 2006).

The goal of this research paper is to visualize the influence of new infrastructure on travel times, so comparing the situation before and after the extension in the transport network is the key task. Raster maps with various spatial discretizations will be used to represent travel times, which restricts map comparison essentially to raster map techniques. According to Salonon and Toivonen (2013), a comparability between different transportation modes can only be significant when all compared travel times are calculated by a door-to-door approach, which means that equal start-end pairs using different transportation modes can be compared while a comparison between two distinct start-end pairs (for example using a new station instead of the previously used one as start) is not helpful in most cases.

Depending on the visualization of travel times, the applicable types of comparison techniques will vary. If there are two separate maps for two scenarios, there are several possibilities for comparing them:

- Displaying the maps next to each other (juxtaposition). A possible addition is to synchronize the cursor on both maps in an interactive environment to ease orientation.
- Different kinds of overlays that combine both scenarios in one map. Differences between the scenarios can be highlighted.
- Slider to move one map over the other. The user can slide to positions where he wants to discover differences between the scenarios.
- Zooming lens that shows the other map. While the cursor is moved over the first map, the same position in the second map is shown in a lense next to the cursor.

As result of a user study, Lobo et al. (2015) show that a transparent overlay of two equally georeferenced maps is the most effective way of making differences visible to the user compared to sliders, lenses or juxtaposition.

Another way of visualizing the differences between two scenarios is not to create two maps but instead directly visualize the differences in one map. In practice that could for example mean computing the difference between two isochrones so that only the area will be visualized that can be additionally reached by the simulated infrastructure but not by the existing one.

Most of the previous research on map comparison techniques was focused on finding differences in urban development by comparing e.g. cadastral maps and aerial images. Since there is still a research gap in map comparison regarding accessibility zones and travel times, this article aims to add new findings to this field.

2.4 Transport Planning Using GIS Techniques

During the last 10 years, several publications on transport planning using GIS techniques were released. The basic idea in most of these is to quantify effects of simulated changes in the existing transport network. Jaepinen et al. (2013) show the influence of a simulated bikesharing system in the city of Helsinki by using maps that illustrate the potential relative time saving with shared bikes in the road network. The calculation depends on the definition of points of interest distributed over the city which work as start and target locations for the computation of shortest connections. The influence of changes in bus connections is analyzed by Brand et al. (2017), distinguishing between different modifications like separated bus lanes or higher frequency and their very own results for the potential usage. Fransen et al. (2015) proposes a technique for finding gaps in public transport accessibility based on the calculation of local indices for needs and provision in northern Belgium. While most shortest path computations are based on single criteria algorithms, Kujala et al. (2018) present a pareto-optimal (multi-criteria) calculation that is able to take the number of changeovers on a single trip into account and display the differences between various optimization criteria in map comparisons.

3 Methodology

The workflow for creating the proposed travel time maps consists of a part executing GIS operations to set up the data (Sect. 3.1) and a visualization part that is done by applying mapping techniques in QGIS (Sect. 3.2) following the guidelines of Schiewe (2023a, 2023b, 2023c).

3.1 Data Preparation and Calculation of Travel Times

The city of Bonn and the surrounding municipalities offer plenty of free spatial data including shapefiles representing the road network, positions of important infrastructure and GTFS-datasets containing the public transportation timetables. Background maps are obtained from OpenStreetMap (www.openstreetmap.de) and Stamen maps (www.maps.stamen.com). The standard GTFS files had to be customized using text processing tools to implement the new connections mentioned in the introduction. Bonn is part of the

public transport network Verkehrsverbund Rhein-Sieg (VRS), which includes Cologne and many more municipalities. The standard GTFS data for the VRS area is given for the whole network, cropping of the data was done for performance reasons. Using the GTFS timetable data, a graph structure is being build based on the time-expanded model according to Pyrga et al. (2008). As displayed in Fig. 1, each station consists of arrival, transfer and departure nodes. The single nodes and also the stations represented by the nodes are connected through edges which represent route segments of public transport lines. This structure allows the application of a shortest path algorithm between given nodes based on Dijkstra's algorithm (Dijkstra et al. 1959). The most common application would then be to display a single shortest path directly on a map, e.g. in a navigation system. Since a single route is not a satisfactory result for the given application, a large set of shortest paths is calculated with the result being a list of travel times to reachable target nodes distributed over the road network. Therefore, a single function call of Dijkstra's algorithm is sufficient to handle all nodes in the network given a specific boundary (e.g. bounding box or highest travel time) which makes the task solvable efficiently.

3.2 Creating Area-Wide Travel Time Maps

Given a list of geo-located points with their calculated travel times from the same starting location, a map can be created by different visualization techniques using layer-based mapping software. A first naive approach would be displaying the travel times as point signatures using a colorscale based on the travel time values. As a background map for orientation, the local road network is visualized in form of grey-shaded line signatures with variable widths depending on the respective road grade and the river Rhine as area signature in blueish grey according to the fundamental definitions of Schiewe (2023b). A similar background map will be consistently used in the following Figures just varying the level of detail depending on the map scale. The use of point signatures for displaying travel times leads to results like the example in Fig. 2a where public transportation stops have been chosen as target points. Since the point density is relatively low, the result lacks information on large parts of the map.

Increasing the point density is possible by extending the list of target points to e.g. all nodes in the road network. The example in Fig. 2b already gives a good impression of the travel time distribution across the whole map but a representation through closed surfaces is purposed instead of single points. A first approach, therefore, is creating octilinear isochrones for prescribed travel time bounds according to Forsch et al. (2021). In the example in Fig. 3, the isochrones for a total travel time of 20 min are shown for the public

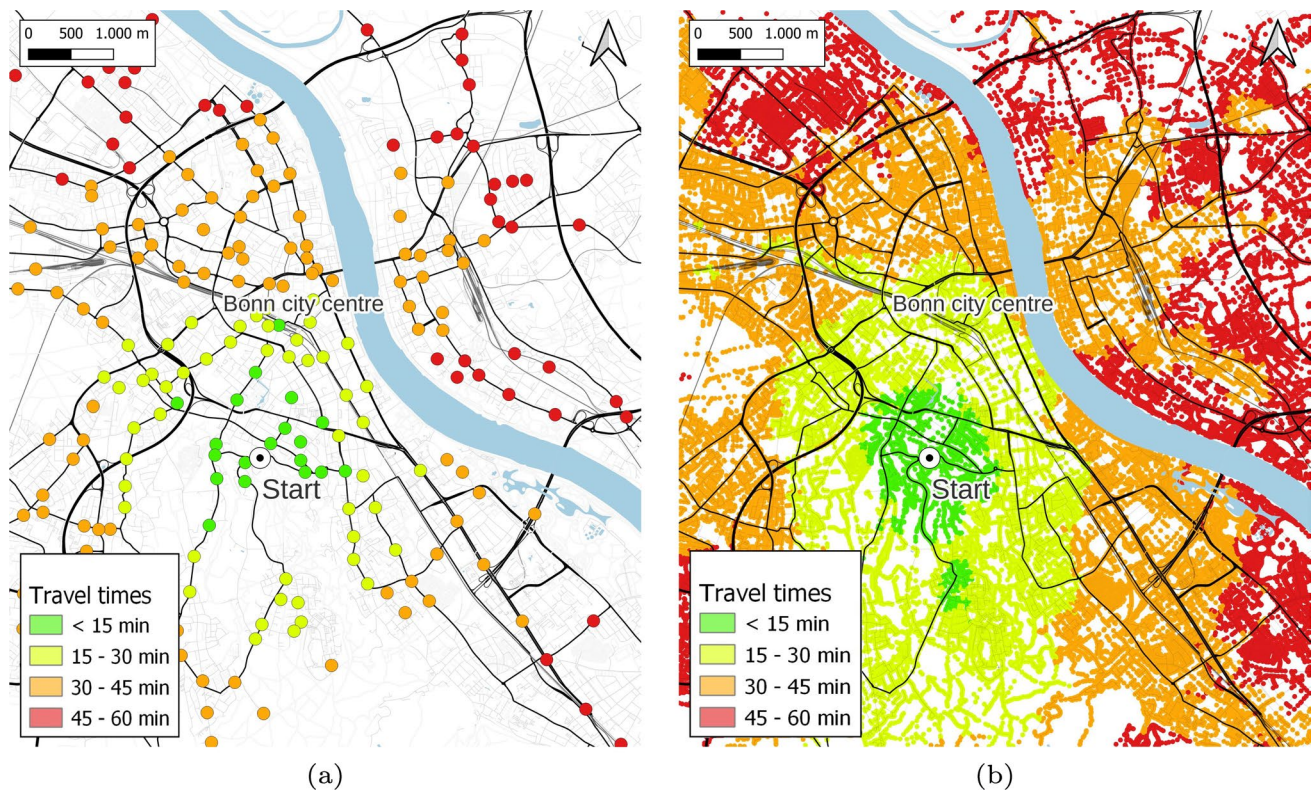
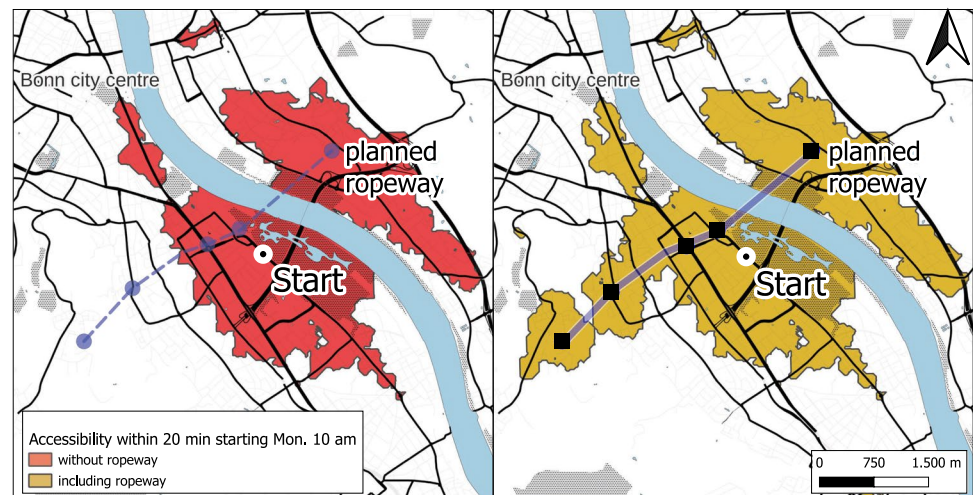


Fig. 2 a) Travel times to public transportation stops. b) Travel times to nodes in the road network

Fig. 3 Accessibility visualized using an octilinear isochrone approach for 20 min maximum travel time, Starting point near Rheinaue on a Monday at 10 am. Left: without ropeway, right: with ropeway



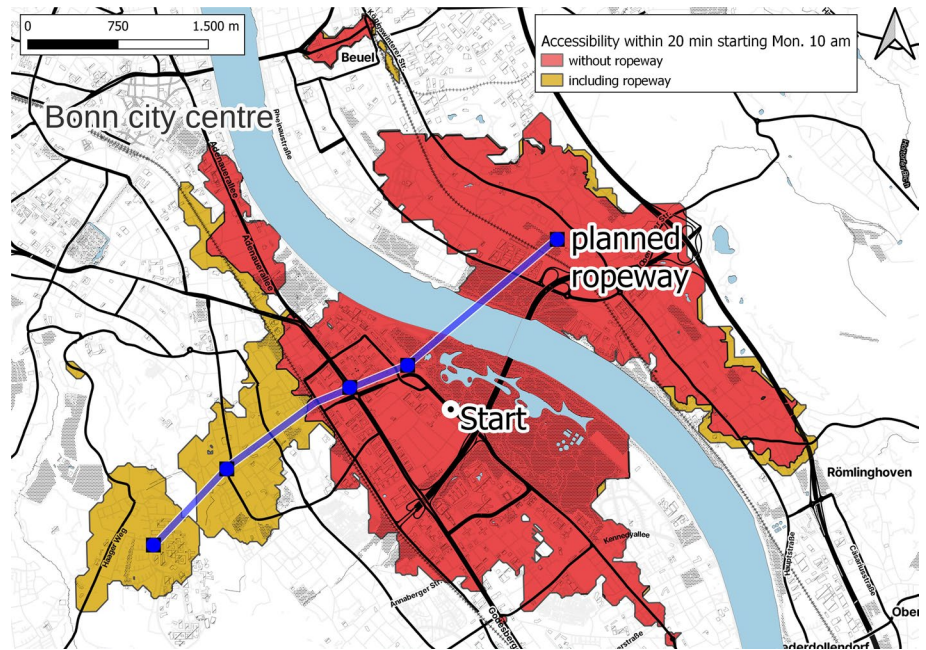
transport network with and without ropeway. Although the same type of content is visualized in both cases (left and right), different colors in the map will be used to illustrate the relation to the view in Fig. 4 which shows the same accessibility zones using an overlay instead of juxtaposition.

Respecting the finding of Lobo et al. (2015), that an overlay improves map comparison compared to juxtaposition, an alternative representation of the isochrones in one map is shown in Fig. 4.

Although the use of isochrones enables a good impression on the influence of new infrastructure for a specific time, it lacks universally valid information for different starting times and of different travel times within the accessibility zone. Therefore, instead of directly calculating isochrones out of the points in Fig. 2, additional processing steps are introduced:

1. Choose a polygonal subdivision of the considered area.

Fig. 4 Accessibility with and without ropeway visualized using an overlay of octilinear isochrones for 20 min maximum travel time. Starting point near Rheinaue on a Monday at 10 am



2. Iterate over all polygons. Find all points in each polygon and calculate the mean travel time.
3. If there are no points in a polygon, use the mean travel time of all neighbored polygons plus an additional travel time depending on the grid size. 1 km can be covered in roughly 15 min of walking, so for a grid size of $400m \times 400m$ the additional time is 8 min (rounded for the longest possible straight line within one cell which is 566 m). If the grid size is unknown or strongly varying, an additional time of 15 min will be used.

4. Save all polygons with their travel times in a file for further processing.

An example result for the suggested processing step is shown in Fig. 5 a, b using an artificial rectangle grid sized $400m \times 400m$ (roughly the size of a block of buildings in between main roads) and a shapefile of all electoral constituencies of Bonn for mapping the points. In the US, census blocks would be a valid spatial discretization (Yin et al. 2015), but also a hexagonal grid or other units can be reasonable choices depending on the intended application

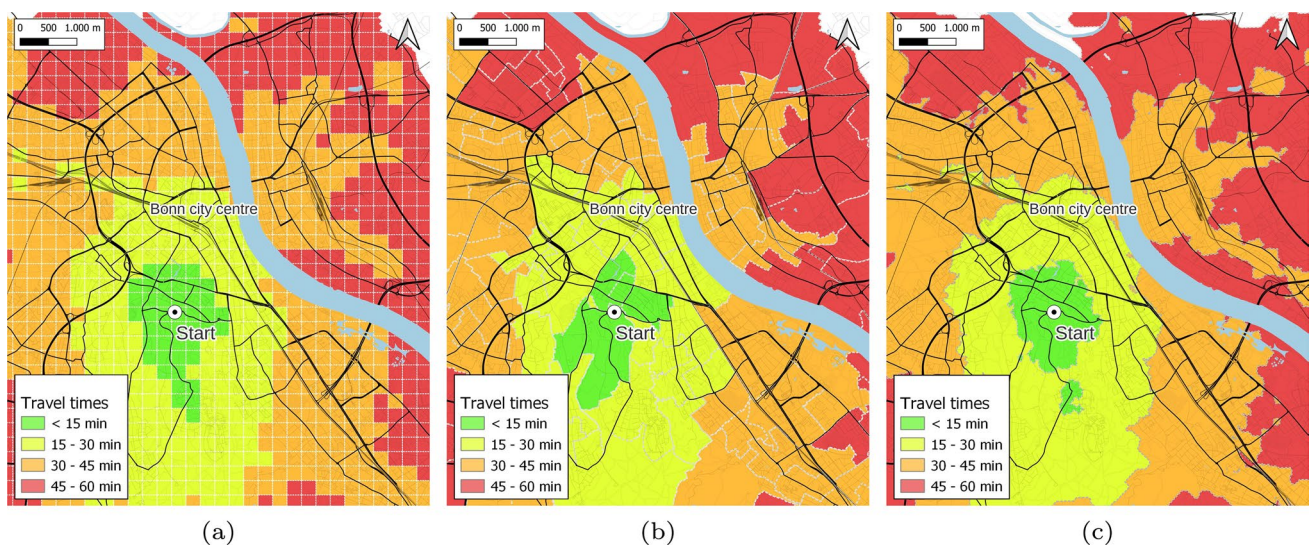


Fig. 5 Point-wise travel times mapped to a) artificial rectangle grid sized $400m \times 400m$, b) electoral constituencies of Bonn, c) octilinear isochrones according to Forsch et al. (2021)

and spatial resolution. For comparing, the exact approach by Forsch et al. (2021) is displayed in Fig. 5c. In accordance with the references of Schiewe (2023c), for all three maps in Fig. 5 (and the other similar figures in this article), the same colormap from green to red is used for displaying travel times as thematic area signatures. These high-contrast colors were chosen to allow a clear visual distinction between the different value ranges. Since green is often related to positive aspects such as a low travel time and red to negative aspects such as a high travel time (e.g. traffic lights, navigation systems with traffic information), these colors are used for the lowest and highest values. The scale in between is covered by yellow and orange which mean a slightly raised but not the highest travel time. Another aspect, which is valid not only for Fig. 5 but all maps in this article, is that the map is a combination of qualitative symbols and quantitative content in different forms. Generally, a simple representation of the local road network and waters (here the river Rhine) is used as a background layer, since this strongly improves spatial orientation in the map through the relation to distinct geometric objects (Schiewe 2023c). For the maps in this article, motorways and important main roads are illustrated with a higher width and in black while small roads are represented thin and grey so that the map does not get overcharged with unnecessary information. Boundaries between single colored cells are displayed by white dashed lines. The main difference in between the three variants in Fig. 5 is that isochrones merge all points in one zone given a specific limit whereas grid cells each contain their own value. This allows further analysis of travel times and travel time differences in multiple scenarios per grid cell which is the foundation for the used map comparison technique in this article.

3.3 Relative Time Savings Visualized in Maps

Until here, one fix starting location and point in time was chosen. To make more general implications on the effects of new infrastructure, it is important to also generalize these parameters. The goal is now to calculate travel time measures separated by grid zones, depending on the influence of the new infrastructure but not on a starting time. The idea is inspired by Fransen et al. (2015), who developed a mathematical index for the public transport demand in spatial zones in northern Belgium. Their basic idea is to calculate averaged travel times between different points of interest and combine them with weighted demographic data in a mathematical model. To make the accessibility index in this article directly visualizable as travel times in maps, the consideration of demographic data will be neglected. The accessibility index AI per grid zone g using the starting point(s) p is defined as follows for covering 192 routes on 1 day between 6 am (360 min) and 10 pm (1320 min) with TT being the travel time average within g at specific time t :

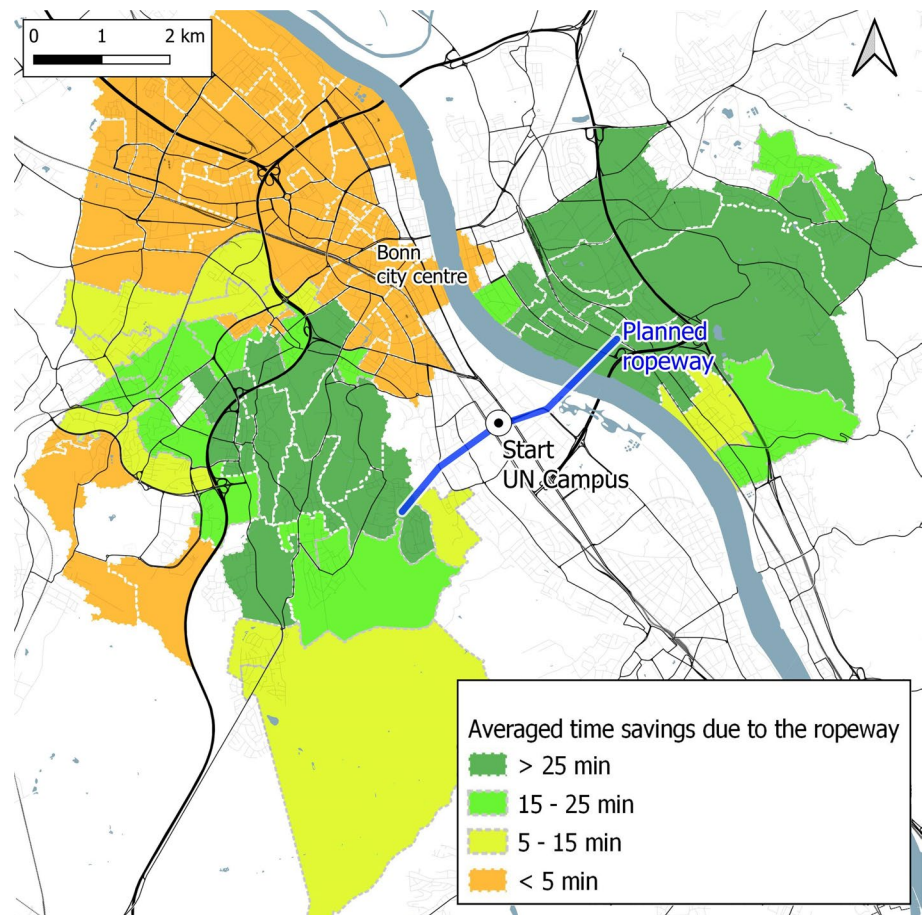
$$AI_{g,p} = \frac{\sum_{t=360\text{min}, t=t+5}^{1320\text{min}} TT(t, g, p)}{192}$$

Shortly summarized, the algorithm for solving this task works as follows:

1. Set one or multiple starting locations and create a dummy node in the graph representation of the road network that has edges to the starting location(s). Dummy node means a node in the graph that has no spatial relation to the real road network but edges with zero travel costs. Executing the shortest path algorithm starting from this node is a simplification which allows to actually use multiple starting locations.
2. Create a list of all network nodes in the considered region with an initial (high) value for the accessibility index.
3. Run a loop starting every 5 min for a whole day between 6 am and 10 pm (frequency and time window can be adjusted).
4. Run Dijkstra's algorithm starting from the dummy node in every loop iteration.
5. Update the index for every node by summing the travel time in the current iteration.
6. After the end of the loop, divide the indices by the number of iterations to get indices that represent the mean travel time during the given time window. Delete points that were unreachable during the calculation of travel times.

The choropleth map in Fig. 6 is an example that displays differences of the mean accessibility indices between a run with the extended GTFS dataset and the common dataset calculated by the presented algorithm for the electoral constituencies according to Fig. 5b. In this case, the start was set at the station UN Campus which is one of the ropeway stations. The colors in the caption are scaled by the time saving due to the implementation of the ropeway. In this case, the dark red color from Fig. 5 was not used since red is often associated with negative impacts but the influence of new infrastructure on travel times can not be negative in the sense of increasing travel times. Therefore, no color, respectively, white as in large parts of the south of Bonn indicates that the mean travel times with and without ropeway differ by less than one minute. The remaining colors range from orange (low time saving) over yellow to two different shades of green which mean higher time savings. Since Bad Godesberg, which is located in the south of Bonn, has a good train connection to UN Campus, it is no surprise that the ropeway would have no impact here. In the north of Bonn, there are large parts with low average time savings between 1 and 5 min. The largest impact of the ropeway can be seen near its end stations on the Venusberg and in Ramersdorf.

Fig. 6 Mean travel time differences (with ropeway/without ropeway) to the electoral constituencies averaged over a full day between 6 am and 10 pm. Starting point at UN Campus



Average time savings of 25 min and more in these areas can be proved by this representation. This result matches the expectations since the end stations of the ropeway can be reached within a few minutes starting at any ropeway station according to the simulated timetable.

As an example covering a larger area, the impact of the extended railway line S13 on the accessibility of the Cologne-Bonn airport is estimated. Since travel times using the S13 are interesting for a larger region compared to the ropeway, an area around Bonn including Rhein-Sieg-Kreis and the airport in the north were included in the visualization. The spatial discretization was done using postal code areas, which cover larger territory than electoral constituencies, on the right side and an artificial rectangle grid on the left side (cf. Figure 7).

Figure 7 shows that a smaller grid size reveals more detailed information about local differences in the averaged travel time savings. Depending on the density of target points, the artificial grid can be adjusted to fit the requirements of different questions in transport planning.

Another interesting addition is the use of multiple starting locations at once. Since the ropeway is designed for improving the accessibility of the university medical center Venusberg, it is especially interesting to analyze the influence of

the ropeway on travel times from or to the hospitals of Bonn. For Fig. 8, all ten hospitals in the city of Bonn have been used, meaning that the mean shortest travel time from any hospital in Bonn was calculated to each electoral constituency. Mean shortest travel time means that each single route between a hospital and the particular target position is the fastest one among all ten routes between the hospitals and the target. All of these single fastest routes were then averaged in the end. Since typical public transport lines always are driving in both directions, this is also an approximation for travel times in the opposite direction from the electoral constituencies to the hospitals. Again, the differences between a run including the ropeway and a run without the ropeway have been calculated. The hospitals are pictured as point signatures in form of red-white crosses in the map.

As recent cartographic literature has shown, the visualization of two equally georeferenced datasets can also be done within one map by using a legend with two dimensions (Strode et al., 2019; Teuling et al., 2010; Hruby, 2015). The data used for Fig. 6 was therefore also used for a bivariate choropleth map (cf. Figure 9). The combination of absolute travel time scopes for both the real and extended network makes it possible to find out the areas affected by different time savings as well as keeping

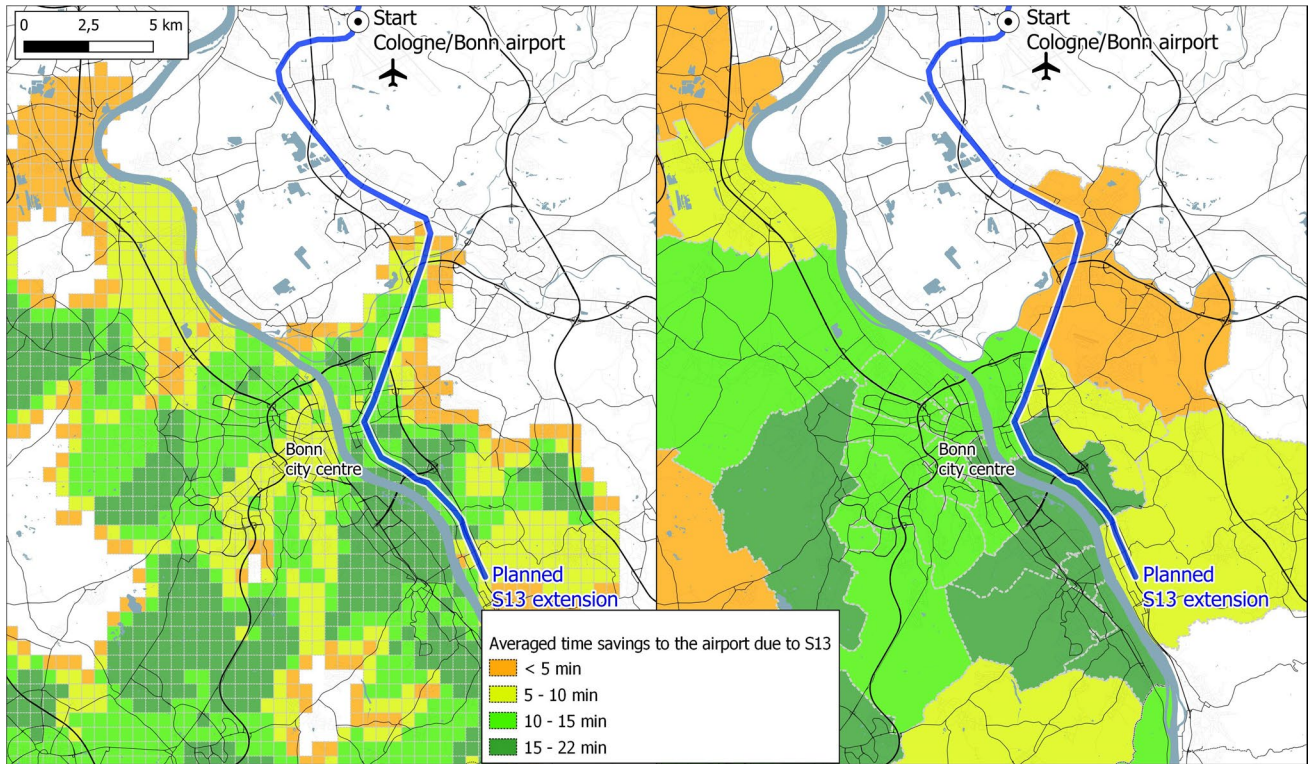


Fig. 7 Differences in mean travel times (with S13/without S13) starting at the Cologne-Bonn airport. Left: rectangle grid, right: postal code areas. Travel times averaged over a full day between 6 am and 10 pm

Fig. 8 Differences in mean travel times (with ropeway/without ropeway) to electoral constituencies from the respective nearest hospital

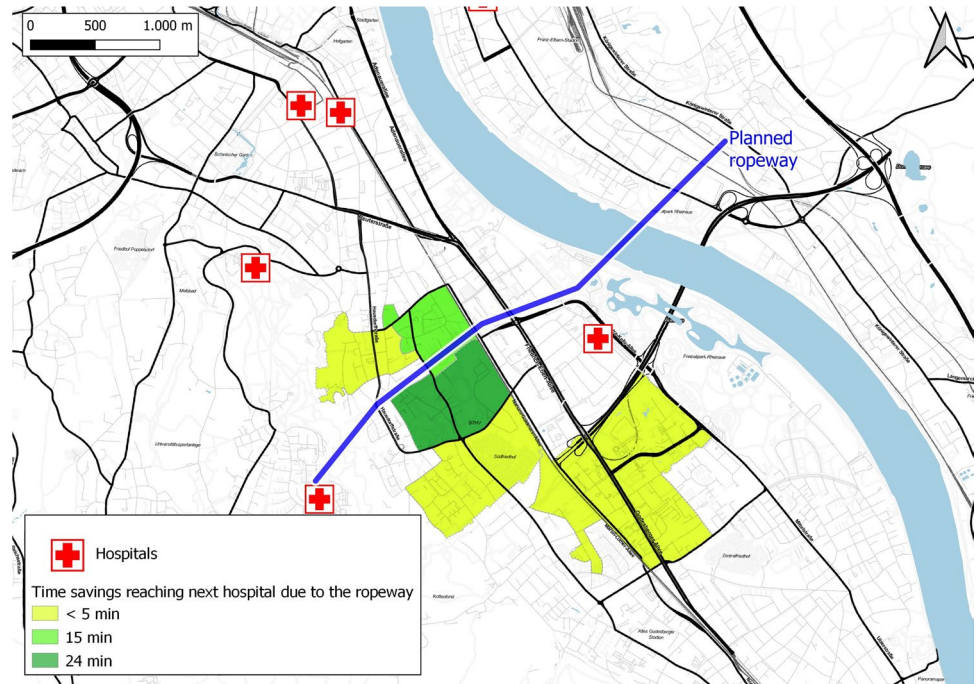
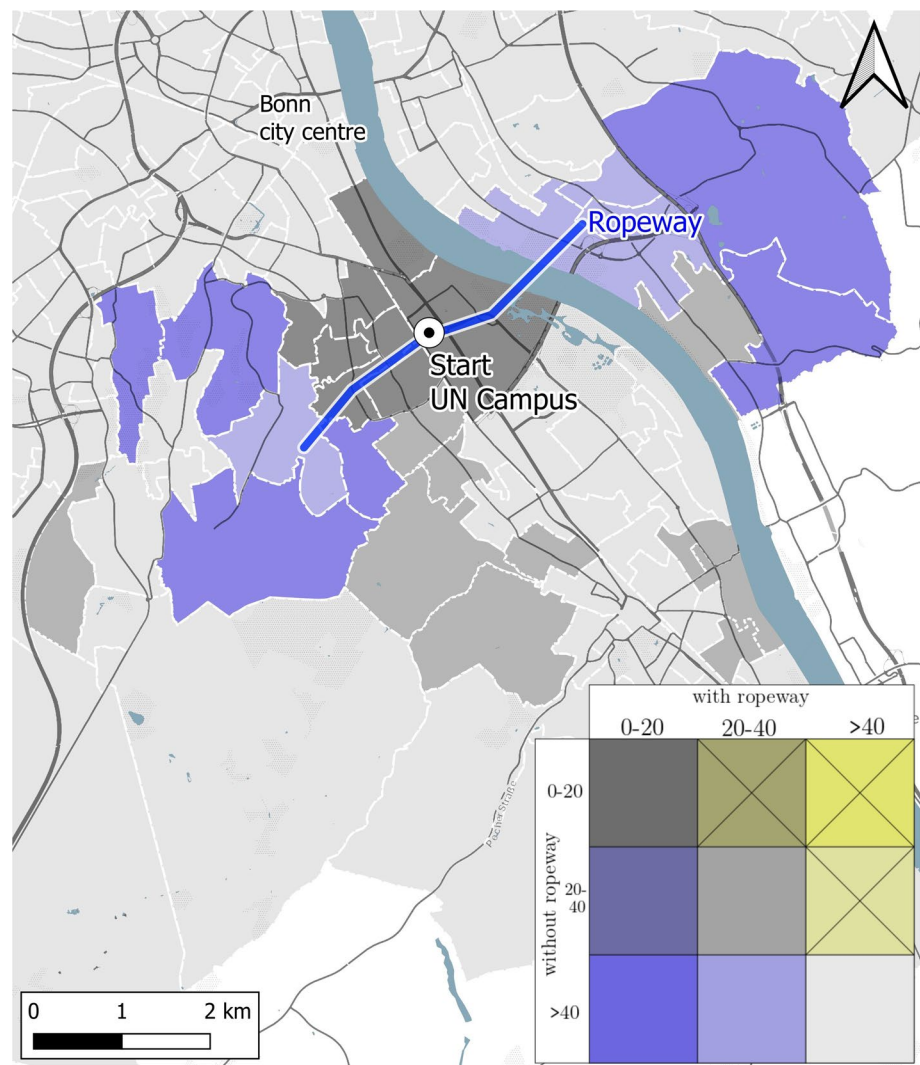


Fig. 9 Differences in mean travel times (with ropeway/without ropeway) starting at UN Campus to electoral constituencies. Averaged over a full day between 6 am and 10 pm. Represented as bivariate choropleth map with a 2D colorscale similar to Lucchesi and Wikle (2017)



an overview over absolute travel times. In this case, a colormap according to Lucchesi and Wikle (2017) was used to represent zones where significant time savings are obtained. The colors in the upper right triangle in the legend (shades of yellow) do not appear since the simulated infrastructure does not lower any travel times.

The bivariate choropleth map for visualizing the influence of new infrastructure on travel times can be seen as a useful tool when absolute travel times need to be integrated in the map. Main disadvantage is that the user can not be sure if the areas colored by the main diagonal colors are actually affected by time savings or not (e.g. the difference between 10 and 15 min would not get detected in Fig. 9). One possible consequence could be to extend the legend to 4×4 or larger to create smaller time ranges but this would also disimprove the readability.

4 Discussion

The main research goal of this article was to analyze existing approaches for the visualization of travel times and to develop new formats especially for the comparative representation of travel times in maps including simulated infrastructure in the data. The literature review in Chapter 2 showed that there are several existing techniques for travel time maps, which are also embedded in free software in some cases, and map comparison techniques that are suitable for the topic at hand. However, only a very small number of literature resources on visualizing the influence of new mobility infrastructure was found during research which made further investigations meaningful and important.

The essence of this publication is the visualization of averaged travel time savings due to new infrastructure discretized by electoral constituencies or other spatial units. The most important benefit of this method compared to recent common approaches such as isochrones, is that no map comparison between different cases (before and after building a new line, different starting times, etc.) is necessary anymore, but the scenario comparison can happen within one map instead. Secondly, it can be clearly distinguished which areas, depending on the respective spatial unit, are affected by which dimension while the legend can always be adjusted. The method is scalable for larger metropolitan regions as Fig. 7 showed and can be applied in any region in the world as long as the data availability is ensured. It also provides the possibility to create more specialized maps such as the hospital accessibility map in Fig. 8 and is suitable for many different use cases and user groups.

Comparing the results to the findings of earlier research in this field such as Fransen et al. (2015), our method does include not-yet existing public transport offers in form of simulated timetable data. While Fransen et al. (2015) propose a method to calculate an abstract measure for public transport needs and offers and display the resulting gap in a map, we directly investigated the changes in travel times through implementing new lines in existing public transport networks. To further examine which map representations are the most appropriate for which purpose and type of users, additional research is needed.

5 Conclusion

The goal of developing a method for visualizing the influence of new public transport infrastructure on travel times was achieved. Our method is based on the simulation of timetable data which is jointly incorporated in a computational model together with real schedules and the underlying road network. The resulting maps can directly feature travel time savings or improvements in the accessibility of points of interest discretized by different spatial units. The proposed technique can be applied to many different scenarios, is scalable and adjustable and creates high potential for further extensions and different applications. The practical use of the maps should be evaluated within user studies.

6 Outlook

The suggested visualization techniques are also suitable for every other region in the world where the necessary data is available and could therefore contribute to mobility planning in many other cases beyond Bonn or Germany. The used data and software also allow many other considerations such as

the accessibility at the user position, different starting times or averaging time frames, the integration of live traffic data, removing existing public transport lines or simulating the use of bicycles, e-scooters and similar by varying the speed of motions. In addition to the hospital accessibility in Fig. 8, it is worth considering cash points, supermarkets, doctors, citizen centres and other points of interest or to combine them all in a large dataset and calculate an abstract mobility index with and without the investigated mode of transportation. The aspiring use of animated and interactive maps (Dijk et al. 2014; Appert et al. 2010; Boettger et al. 2008) could also play a role in combination with travel time analysis. Giving the user the option to interactively set the starting position for an instant calculation of the corresponding travel time scenario with adjustable starting time could be a very helpful tool for fast and straightforward mobility planning. A simple zooming option or a lense that enables for example a smaller rectangle grid within a representation by postal code areas to reveal more details would be another desirable extension. Generally, it is important to adapt maps to the particular user group and intention, some of the proposed maps might not be suitable for public communication purposes and should only be considered in planning by experts. However, there is still a necessity for continuous research on this topic to prove the applicability of the presented concepts, e.g. by task-based user studies (Lobo et al. 2015) or studies based on subjective criteria such as readability and usability (Wielebski and Medyńska-Gulij 2023).

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Compliance with Ethical Standards

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References

- Ahmed M, Fasy BT, Hickmann KS et al (2015) A path-based distance for street map comparison. *ACM Trans Spat Algorithms Syst (TSAS)* 1(1):1–28
- Allen J (2018) Using network segments in the visualization of urban isochrones. *Cartographica Int J Geogr Inf Geovisualization* 53(4):262–270
- Appert C, Chapuis O, Pietriga E (2010) High-precision magnification lenses. In: *Proceedings of the SIGCHI conference on human factors in computing systems*, pp 273–282
- Bast H, Carlsson E, Eigenwillig A, et al. (2010) Fast routing in very large public transportation networks using transfer patterns. In: *Algorithms—ESA 2010: 18th annual european symposium, Liverpool, UK, September 6–8, 2010. Proceedings, Part I 18*, Springer, pp 290–301
- Boettger J, Brandes U, Deussen O et al (2008) Map warping for the annotation of metro maps. *IEEE Comput Graphics Appl* 28(5):56–65
- Bolzoni P, Helmer S, Lachish O (2016) Fast computation of continental-sized isochrones. In: *International conference on GIScience short paper proceedings*
- Brand J, Hoogendoorn S, Van Oort N, et al. (2017) Modelling multimodal transit networks integration of bus networks with walking and cycling. In: *Proc. 5th IEEE international conference on models and technologies for intelligent transportation systems (MT-ITS)*, pp 750–755
- Dijk TCV, Goethem AV, Haunert JH, et al. (2014) Map schematization with circular arcs. In: *International conference on geographic information science*, Springer, pp 1–17
- Dijkstra EW et al (1959) A note on two problems in connexion with graphs. *Numer Math* 1(1):269–271
- Foody GM (2007) Map comparison in gis. *Prog Phys Geogr* 31(4):439–445
- Forsch A, Dehbi Y, Niedermann B et al (2021) Multimodal travel-time maps with formally correct and schematic isochrones. *Trans GIS* 25(6):3233–3256
- Frank L, Bradley M, Kavage S et al (2008) Urban form, travel time, and cost relationships with tour complexity and mode choice. *Transportation* 35(1):37–54
- Fransen K, Neutens T, Farber S et al (2015) Identifying public transport gaps using time-dependent accessibility levels. *J Transp Geogr* 48:176–187
- Gartner G, Radoczky V (2005) Schematic vs. topographic maps in pedestrian navigation: How much map detail is necessary to support wayfinding. In: *AAAI spring symposium: Reasoning with mental and external diagrams: computational modeling and spatial assistance*, pp 41–47
- Hagen-Zanker A (2006) Map comparison methods that simultaneously address overlap and structure. *J Geogr Syst* 8(2):165–185
- Hansen WG (1959) How accessibility shapes land use. *J Am Inst Plan* 25(2):73–76
- Hart PE, Nilsson NJ, Raphael B (1968) A formal basis for the heuristic determination of minimum cost paths. *IEEE Trans Syst Sci Cybern* 4(2):100–107
- Hruby F (2015) Applications of bivariate choropleth maps. In: *15th international multidisciplinary scientific geoconference SGEM 2015*, pp 705–712
- Jaepinen S, Toivonen T, Salonen M (2013) Modelling the potential effect of shared bicycles on public transport travel times in greater helsinki: an open data approach. *Appl Geogr* 43:13–24
- Kamw F, Al-Dohuki S, Zhao Y et al (2019) Urban structure accessibility modeling and visualization for joint spatiotemporal constraints. *IEEE Trans Intell Transp Syst* 21(1):104–116
- Knight B (2004) Parochial interests and the centralized provision of local public goods: evidence from congressional voting on transportation projects. *J Publ Econ* 88(3–4):845–866
- Kujala R, Weckstroem C, Mladenovic MN et al (2018) Travel times and transfers in public transport: comprehensive accessibility analysis based on pareto-optimal journeys. *Comput Environ Urban Syst* 67:41–54
- Lilienthal H, Itter C, Schnug E (2007) Anwendung von Ähnlichkeitsmaßen zum Vergleich landwirtschaftlicher Geoinformationen, *Bundesforschungsanstalt für Landwirtschaft*, pp 48–55
- Liu S, Zhu X (2004) An integrated gis approach to accessibility analysis. *Trans GIS* 8(1):45–62
- Lobo MJ, Pietriga E, Appert C (2015) An evaluation of interactive map comparison techniques. In: *Proceedings of the 33rd annual ACM conference on human factors in computing systems*, pp 3573–3582
- Lucchesi LR, Wikle CK (2017) Visualizing uncertainty in areal data with bivariate choropleth maps, map pixelation and glyph rotation. *Stat* 6(1):292–302
- Morgan M, Young M, Lovelace R et al (2019) Opentripplanner for r. *J Open Source Softw* 4(44):1926
- Nobis C, Obersteller D, Klein-Hitpass A, et al. (2020) Städte in bewegung. Zahlen, daten, fakten zur mobilität in 35 deutschen städten
- Pyrga E, Schulz F, Wagner D et al (2008) Efficient models for timetable information in public transportation systems. *J Exp Algor* 12:1–39
- Salonen M, Toivonen T (2013) Modelling travel time in urban networks: comparable measures for private car and public transport. *J Transp Geogr* 31:143–153
- Schiewe J (2023) Kartenlayout. *Kartographie: Visualisierung georäumlicher Daten*. Springer, Berlin, pp 351–364
- Schiewe J (2023) Kodierung von thematischen Informationen. *Kartographie: Visualisierung georäumlicher Daten*. Springer, Berlin, pp 285–306
- Schiewe J (2023) Mittel zur Kodierung. *Kartographie: Visualisierung georäumlicher Daten*. Springer, Berlin, pp 215–267
- Schoedon A, Trapp M, Hollburg H, et al. (2016) Interactive web-based visualization for accessibility mapping of transportation networks. In: *EuroVis (Short Papers)*, pp 79–83
- Strode G, Morgan JD, Thornton B et al (2019) Operationalizing trumbo’s principles of bivariate choropleth map design. *Cartogr Perspect* 94:5–24
- Teuling A, Stöckli R, Seneviratna S (2010) Short communication bivariate colour maps for visualizing climate data. *Int J Climatol*
- Tversky B (2000) Some ways that maps and diagrams communicate. *Spat Cognit* II:72–79
- Visser H, De Nijs T (2006) The map comparison kit. *Environ Modell Softw* 21(3):346–358
- White R (2006) Pattern based map comparisons. *J Geogr Syst* 8(2):145–164
- Wielebski Ł, Medyńska-Gulij B (2023) User evaluation of thematic maps on operational areas of rescue helicopters. *ISPRS Int J Geo-Inf* 12(2):30
- Yin S, Li M, Tilahun N, et al. (2015) Understanding transportation accessibility of metropolitan chicago through interactive visualization. In: *Proceedings of the 1st International ACM SIGSPATIAL Workshop on Smart Cities and Urban Analytics*, pp 77–84
- Young M (2018) Opentripplanner-creating and querying your own multi-modal route planner. <https://github.com/marcusyoung/otp-tutorial/blob/master/intro-otp.pdf>