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REGULAR PAPER

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The public transport navigation system

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Abstract Public transport maps are typically designed in a way to support route finding tasks for passengers, while they also provide an overview about stations, metro lines, and city-specific attractions. Most of those maps are designed as a static representation, maybe placed in a metro station or printed in a travel guide. In this paper, we describe a dynamic, interactive public transport map visualization enhanced by additional views for the dynamic passenger data on different levels of temporal granularity. Moreover, we also allow extra statistical information in form of density plots, calendar-based visualizations, and line graphs. All this information is linked to the contextual metro map to give a viewer insights into the relations between time points and typical routes taken by the passengers. We also integrated a graph-based view on user-selected routes, a way to interactively compare those routes, an attribute- and property-driven automatic computation of specific routes for one map as well as for all available maps in our repertoire, and finally, also the most important sights in each city are included as extra information to include in a user-selected route. We illustrate the usefulness of our interactive visualization and map navigation system by applying it to the railway system of Hamburg in Germany while also taking into account the extra passenger data. As another indication for the usefulness of the interactively enhanced metro maps we conducted a controlled user experiment with 20 participants.

Keywords Public transport maps · Information visualization · User study · Interaction techniques · Route computation · Navigation system

1 Introduction

Traveling in a foreign city typically requires inspecting a public transport map (Netzel et al. 2017b) placed at a metro station's wall, in a travel guide, on carriage walls, on the web, or on a smart phone. The major goal of those maps is showing the most important information like the metro stations, lines, or interchange points (Burch et al. 2016), and in some cases additional features like famous sights, rivers, or airport locations (Woods 2019).

The 'old-fashioned' maps try to focus on an uncluttered and aesthetically looking appearance by distorting the stations in a way that the exact geographic position is not given anymore, but the topology is still preserved to a high degree. This layout strategy allows to reclaim space that would be wasted if the exact

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geographic positions of the stations were used. Moreover, many aesthetic drawing criteria are followed (Lloyd et al. 2018) to generate readable, understandable, and intuitive maps. The design of public transport maps is still an ongoing story since the transport systems grow larger and larger in complexity and also provide more and more ways to travel in a city in an interconnected way.

Unfortunately, although they are mostly well designed, they do not allow interactions nor do they show extra dynamic information about the passengers like number of people in a certain train at a certain time point (Burch et al. 2016). Actually, it may be important to see how many people enter or leave a train at a certain metro station to better plan a journey for example. Getting extra views for this kind of data integrated in and aligned with the public transport map as well as side-by-side interactive and linked perspectives can help to find the best traveling route for a passenger at a certain point in time, for example avoiding crowded trains or busy interchange points. Moreover, there is typically no support for travelers to compute routes in a map that follow user-defined criteria and properties like passenger numbers, traveling distances, or famous sights, even for certain points in time. Moreover, extending this idea to several maps instead of one can provide extra automatically generated information for planning a route somewhere that is based on users' intentions, i.e., in scenarios in which the city to travel to is not explicitly known beforehand.

In this paper we illustrate an approach to enhance public transport maps with time-varying passenger data on different temporal granularities. The extra data are attachable to all stations and metro lines. This extension was not possible for public transport maps designed before the invention of the computer (Ovenden 2005), although they have been designed for supporting travelers at route finding tasks for the state-of-the-art at these times (Burch et al. 2014). But, negatively, they typically could not provide integrated or additional side-by-side and linked views on dynamic data like passenger numbers, how many enter or leave the trains at certain metro stations on different levels of temporal granularity, or even interactions with such data in order to find the best traveling route for the passengers. Moreover, integrating the computer with powerful algorithms in the user-specified route identification and recommendation tasks as well builds a powerful concept that is guided from two perspectives—the human user and the machine, while our novel public transport map navigation system builds the interface to communicate between both sides with the goal to find efficient solutions to this problem.

We illustrate the usefulness of our interactive and web-based enhanced public transport maps, the public transport map navigation system, by showing traveling scenarios in the city of Hamburg in Germany, also taking into account famous sights. A user experiment with 20 participants has been conducted to investigate if non-experts in visualization are able to understand the original maps as well as the visually enhanced maps. Moreover, as a major result we found out that the interactive and visually enhanced maps are useful to plan routes in a city by taking into account extra passenger information. The enhanced maps also do not lead to longer completion times compared to the original maps, although we expected this effect due to the increased amount of visual clutter (Rosenholtz et al. 2005). Finally, we discuss scalability issues as well as limitations of our interactive tool based on user feedback and we provide a look into future directions.

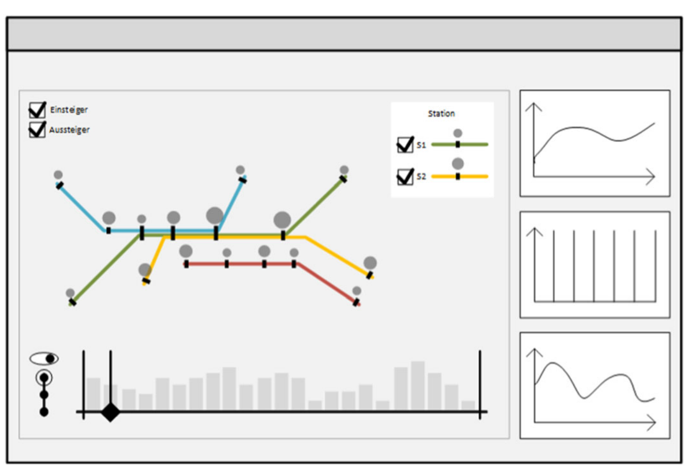


Fig. 1 A public transport map is in the center of the view, while additional passenger information is added to the stations as well as simple histograms and time-series plots provide additional information. Interactions can be applied to inspect the metro map from a user-defined perspective

This paper is an extension of a formerly published paper at the international symposium on visual information communication and interaction (Burch et al. 2020). We extend the original work by several points:

- *Further interaction techniques* We integrated further interaction techniques to the already existing ones (Sect. 3.4).
- *Graph-based view* Apart from the public transport system map, we also support the selection of several connected stations to inspect them as a node-link diagram. This frees the visual representation from the spatial arrangement given by the map layout and allows to generate own station layouts. The number of passengers can be visually encoded in the link thickness (Sect. 3.5).
- *Route comparison* By the graph view, we can interactively select different routes and compare them. Moreover, we can inspect their changes over time as a dynamic graph visualization (Sect. 3.6).
- *Criteria-based automatic route generation* A user can provide criteria as attribute values like maximum number of passengers, travel times, number of stations (length of the route), and so on. Based on that information, a route can be computed automatically, also with varying properties over time like in a navigation system (Sect. 4.1).
- *Sights-based automatic route generation* Also popular sights can be included as extras in the route generation process, for example, generating a route that does not directly lead from a start to a destination but that allows a stop-over close to a given sight's location (Sect. 4.2).
- *Multiple citie* A route can even be generated based on the whole repertoire of cities or a part thereof. If a route is just specified by certain properties like lengths and a number of passengers, the navigation system can compute routes in cities with the desired properties (Sect. 4.3).
- *Limitations* To illustrate the negative issues in our work, we also provide some arguments about limitations, in particular focusing on scalability problems (Sect. 7).

2 Related work

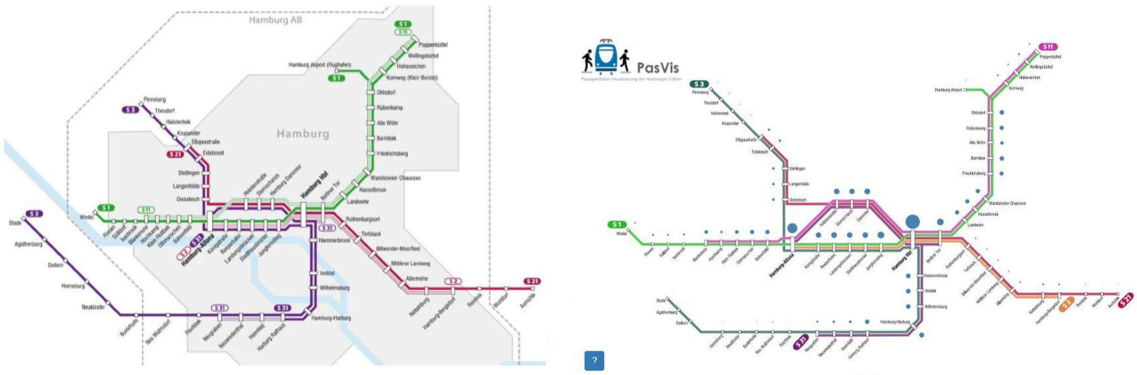
Metro maps have been designed a long time ago since the work by Henry Charles Beck (Garland and Beck 1994) or even earlier by Dow (2005). Actually starting in London with the famous Underground tube map, more and more cities around the globe have been in focus of public transport and hence providing maps to support the travelers.

However, the usefulness of those maps depends on several factors and still some improvements are made. Consequently, there are various studies on map designs, typically looking into geographic maps (-Kiefer et al. 2013). Netzel et al. (2017a), for example, investigated which additional hints support a viewer to find labels. Moreover, Netzel et al. (2017b) also investigated where people pay visual attention when answering route finding tasks in public transport maps and Burch explored the visual attention distribution in public transport maps (Burch 2017b).

A major result shows that people tend to subdivide the task into subtasks (Burch 2017a), follow the geodesic path tendency (Huang et al. 2009), combine all subsolutions, and crosscheck the final solution. However, in these eye tracking studies the authors do not investigate additional time-varying passenger data to enhance those maps and to provide extra information for finding the best route from a start station to a destination station. For example, the passenger data might play a crucial role when choosing a route, to avoid crowded trains at a certain point in time.

Zeng et al. (2014) integrate mobility-related aspects like riding time, transfer time, waiting time, and round-the-clock patterns. Although this is an extension to standard static public transport maps, their work focuses more on the exploration and analysis of passenger mobility by analytical tasks. In our work, we focus more on the enhancement of the map in an intuitive and easy way, designed for the non-experts in data analysis and visualization.

Several researchers (Kunimatsu and Hirai 2014; Marey 1885; Barry and Card 2014; Itoh et al. 2013) investigated the problem of enhancing maps by additional perspectives on extra data sources, for example passenger flows with an additional view on the map. However, those visualizations do not provide extra views on different levels of temporal granularity and might be difficult to be used by the human user which is due to the fact that the provided views are sometimes suffering from visual clutter (Rosenholtz et al. 2005) or combine the views in a way that it might not be trivial anymore to understand them quickly.



(a) (b)

Fig. 2 An original public transport map (Map 2017) (**a**) is enhanced by integrated visual features (**b**). Those features can come in many forms, for example differently large circles attached to the stations to indicate the number of passengers entering or leaving a train at a certain point in time

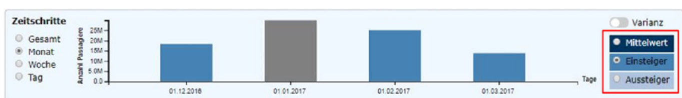
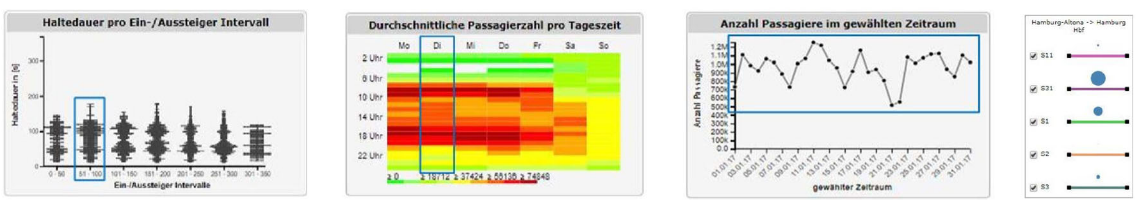
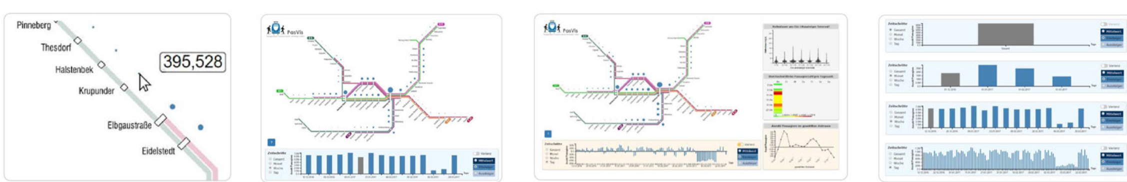


Fig. 3 A simple visualization indicating the number of people entering or leaving a train in a certain time interval



(a) (b) (c) (d)

Fig. 4 Several views are added to the original public transport map to provide more information than the standard metro maps: **a** Density plots, **b** calendar-based matrix visualization, **c** line graphs, and **d** metro line bubbles

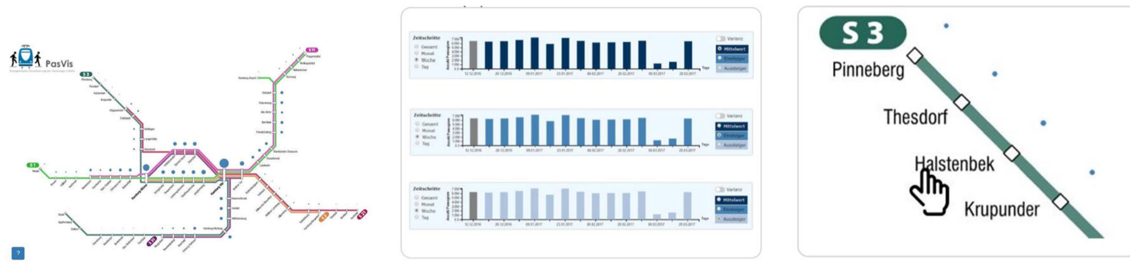


Select (a) Explore (b) Reconfigure (c) Abstract/Elaborate (d)

Fig. 5 Different ways to interact with the visually enhanced public transport maps: **a** Select. **b** Explore. **c** Reconfigure. **d** Abstract/Elaborate

3 Visualization techniques and interactions

The basic visualization is a standard static public transport map that is enhanced by additional views on dynamic passenger data and interaction features. Moreover, extra perspectives on the passenger data are given as simple diagrams, interactively (Yi et al. 2007) linked to the public transport maps (see Figs. 5, 6), to preserve the usability aspect of the enhanced maps for the non-experts in visualization, i.e., the everyday traveler (see Fig. 1 for an illustration of how the enhanced map might look like).



Encode **(a)** Filter **(b)** Connect **(c)**

Fig. 6 Some other ways to interact with the public transport maps: **a** Encode. **b** Filter. **c** Connect

3.1 Maps and passenger data

The passenger data were accessed from the web page *data.deutschebahn.com*, and we exported it in a CSV data format. In this research and for illustrative purposes, we focus on the time period from December 2016 to March 2017 that resulted in more than 600,000 data samples. However, there is no limitation to the time period from which the data are extracted from the online system.

The acquired data have a tabular form consisting of several relevant attributes like train number, start station, number of passengers entering the train, number of passengers leaving the train, arrival time, departure time, destination station, and train line. Before working with the data, we had to identify missing data entries and wrong stopping points.

3.2 Design decisions

We base our visualization tool on a list of design decisions that are also visible in the layout of the graphical user interface (see Fig. 1). Moreover, we integrated visual features in public transport maps (see Fig. 2).

- *Focus on dynamic passenger data* We focus on providing extra views on the time-varying passenger data. This means that travelers looking at the interactive maps should be able to easily understand this information attached to the metro map stations and also given as visual means for filtering the data.
- *Provide several linked views* All the extra views should be interactively linked with the public transport map. This means that a change in any of the views has an impact on the change in all of the other views, helping to understand the direct correspondences between the views.
- *Enhance public transport maps* Looking at standard public transport maps is already helpful to find the metro lines and interchange points to come from a starting station to a destination station. But, extra information on passenger numbers (crowded or empty) trains is typically not available.
- *Use easy-to-understand diagrams* Since the interactive visualization tool is designed for non-experts in visualization, we focus on easy-to-learn and easy-to-use diagrams. Otherwise, travelers might get confused and consequently will not use them for traveling in a city.
- *Support interaction techniques* Public transport maps placed as a poster to a station's wall are typically static depictions of the transport system. In our design, we focus on supporting travelers to interact with all the views in order to find a suitable parameter setting for their tasks at hand.
- *Show different temporal granularities* We also support filtering of the time-dependent data; in particular, we allow different perspectives on the passenger data, for example, by changing the temporal granularity of the data (temporal aggregation).

With the interactive visualization, we focus on answering a list of user-defined tasks like:

- *Train stops* Does a train stop longer at a certain station if more people enter the train?
- *Time points* At what time points of the day is the number of passengers the largest and at which stations?
- *Stations* Are there superfluous stations at which not many passengers enter or leave a train?
- *Outliers* Are there temporal outliers in the sense that at certain time periods really many or only a few passengers travel?

3.3 Data-to-visualization mapping

In this section, we describe how the public transport map and the additional data are visually encoded, i.e., to which visual variables it is mapped. To show all of this information, we provide several views (Roberts 2004) with the public transport map as the largest view.

3.3.1 Metro map view with bubbles

We use color-coded bubbles to indicate the number of passengers entering or leaving a train at a certain station. The sizes of the bubbles proportionally encode the number of people, while the bubbles are always aligned with the stations. Although this produces extra visual features in the map, it also has the benefit to give the passengers insights about which stations are rather crowded with people and at what times during a day (see Fig. 2a, b for the enhanced map with bubbles).

3.3.2 Time histograms

The histograms provide an information about the number of people using public transport on different levels of temporal granularity. We support perspectives on days, weeks, and months as well as an overview about the total number of people using the train. This information can be split into passengers entering a train or leaving it as well as the average value can be displayed together with the variance (see Fig. 3 for an illustration of such a time histogram).

3.3.3 Density plots

For each station, we can have a look at a density plot about the number of people entering or leaving a train as well as the length of a stop of a train. The number of people is hereby given as intervals of size 50 and the stopping times in seconds (see Fig. 4a for an illustrative example and the visual patterns that are created).

3.3.4 Calendar-based matrix visualizations

In the calendar-based visualization (van Wijk and van Selow 1999), we can observe the number of passengers at a certain time of day and at a certain weekday. The color coding is used to indicate the number of people traveling, while a red color reflects the highest number of passengers (see Fig. 4b for an illustrative calendar-based visualization of the number of passengers).

3.3.5 Line graphs

Some non-experts in visualization also prefer a line graph indicating the number of passengers in a certain time period. The time-dependent patterns of the lines easily reflect the traveling behavior. Such a line plot can be computed for every station and also for entering and leaving passengers as well as for different temporal granularities. The vertical axis describes the number in one hundred thousands (see Fig. 4c for an illustrative example of a line graph for a specific user-selected station).

3.3.6 Metro line bubbles

In some cases, it might also be of interest to explore how many people are actually traveling in a train on a certain metro line segment (between two stations) and also at a certain time point during a day. This information can also be shown for different time scales as well as accumulated over all time points indicating the metro line segment on which most people travel over the entire year for example (see Fig. 4d for an illustrative example of the metro line bubbles).

It may be noted that with these simple visualizations and diagrams, the non-expert in visualization can easily navigate and interact in the data. However, the metro map can also be used as a standard map without any extras, for example, for passengers who are actually just trying to find a route and not one focusing on extra passenger data.

3.4 Interaction techniques

To provide and implement a list of useful interaction techniques, we follow the taxonomy by Yi et al. (2007). The users of the interactive and visually enhanced maps should be able to see the map in its original form but also with visual enhancements. If the latter is the case, they should be able to modify several parameters, for example, the temporal granularity of the passenger data, flipping between people leaving or entering the train, filtering for time and number of people, as well as changes in color codings to mention a few. The seven categories for interactions are graphically depicted in Figs. 5a (select), b (explore), c (reconfigure), d (abstract/elaborate), 6a (encode), b (filter), and c (connect).

3.5 Graph view

Since the public transport map is already laid out in a certain way with many extra attached map-specific information, it might be difficult to pay visual attention to a certain user-selected route. For this reason, we support the selection of routes in a public transport map which are then visually represented in a node-link diagram only consisting of nodes and links and being freed from all the extra information.

To reach this goal, the users can select a start and a destination station for which all possible routes are computed, i.e., a connected graph is extracted from this request and visually depicted in a separate window (see Fig. 7 for an example of a selected route preserving the travel direction from the public transport map). The user can layout the graph on demand and move around nodes individually. Moreover, the graph view is interactively linked with the corresponding public transport map which is still required for contextual purposes.

3.6 Visual route comparison

If several selected routes have to be compared, for example to select the most suitable one for a journey, it is a tedious task to do that by means of a public transport map alone. Our navigation system allows to select several routes and visually depicts them as node-link graph visualizations in a side-by-side view with the station identifiers to create an alignment of all of them. Such an alignment helps to better compare the identified routes.

This feature might be helpful to compare the found routes over time. Also different routes from the same city as well as routes from various cities can be compared, for example, in a scenario in which the traveling time is fixed due to the holiday season and the only question is which city is nice to travel at this specific time period. Normally, the best travel time is mostly inspected from other perspectives than the number of passengers in a public transport map as well as additional public transport-specific information.

4 Algorithmic route detection

Apart from the visual map enhancements and the interaction techniques supporting the users, we also integrated a more algorithmic solution into our public transport navigation system. To reach this goal, we implemented a criteria-based algorithm, a sights-based automatic route detection, and a very general route search and identification method taking into account all available cities.

To implement such an algorithm, we model an entire public transport system as a network $G = (V, E)$, where V denotes the stations and E the (directed) line segments in between. To model several relations at the same time, we use a multi-network that allows multiple relations between each pair of vertices (stations), for example, the different metro lines, the passenger number, or the travel time. Moreover, each vertex can be attached by additional properties or objects, for example, number of people entering or leaving the train or

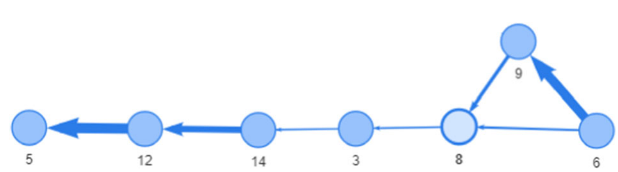


Fig. 7 A graph visualization consisting of nodes and links can show the identified route from a start to a target station without extra visual enhancements. In this case, even the station names have been replaced by number identifiers

even sights. To allow the computation of solutions for a certain time point (to find the best time periods to travel on a day, a week, a month, or a year), we internally store such a multi-network for each time instance, i.e., the edge properties of the graph modeling the public transport system carry a temporal information.

4.1 Criteria-driven approach

When computing suitable routes, we can base that on possible algorithm parameters that might come in the form of maximum number of passengers, travel times, number of stations (length of the route), and many more. Based on that information, a route can be computed automatically, also with varying properties over time like in a typical navigation system. The algorithm only outputs the routes following the user-specified criteria.

The algorithm takes as input a start and a destination station, as well as all additional parameters that should further specify desired routes, for example, maximum route length, number of passengers (in total or on a route segment), travel times, and so on. If just a route without further restrictions is of interest, we can leave all extra information blank. Mathematically, this means that the corresponding route finding algorithm computes all possible routes between start and destination stations first that meet the needs of the users, i.e., a Dijkstra algorithm first generates shortest routes in our multi-network for each time instance attached to the edges (the metro system and the sight information stay stable for each algorithm run). If this shortest path (if there is any) does not meet the needs, the search space for possible solution routes gets enlarged by searching over the entire multi-network. It may be noted that a public transport system is not that complex compared to a general network, and hence, a fast solution is generally expected.

4.2 Including famous sights

As another add-on, we incorporated the most famous sights for each city and the closest public transport map station from which it can be easily reached by foot. This means a user can select a certain number of sights, while the algorithm takes into account the sights when generating possible routes in the public transport system. Combining the sight information with the extra criteria on passenger data for example can help to compute routes meeting the needs of the travelers. However, it may be noted that the more parameters are specified the less likely it becomes to find suitable routes, but the traveler is able to interactively adjust the given parameter values and see which routes are detected by the algorithm.

To include the sights, the route finding algorithm marks certain vertices as absolutely necessary in the final route solution. This extra information is added as vertices that have to be visited while traveling from a start station to a destination station. To reach this goal, the algorithm first generates a possible shortest route including all stations close to the specified sights. After such a route is found, the additional criteria are also taken into account which might limit the number of possible routes, even if the entire time period is included in the route searching process. It may be noted that the extra sight information may lead to longer algorithmic running time due to the fact that the formerly shortest routes are artificially lengthened by the extra travel stops given by the sight information.

4.3 Based on entire city repertoire

Public transport systems of multiple cities have varying properties, but positively, attributes like number of passengers build a common data dimension that can flow into a data analysis process which computes suitable routes. As another algorithmic add-on, we can specify public transport parameters and see which cities an algorithm outputs with routes following these parameter values. Apart from just inspecting the algorithmic solutions, a user can further look into the visual enhancements to see if the algorithmic solution really fulfills the desired criteria.

Mathematically, we can take into account all multi-networks (one for each available city), specify all parameters that we know by omitting the start and destination stations. Finally, the algorithm outputs all possible routes that follow the desired criteria. This feature is in particular of interest if we want to get an overview about possible cities in which the travel times are low in general and also the number of passengers at certain time points or periods. The output of such an algorithm hence gives some kind of preselection for cities and travel periods that the users can incorporate for their next holiday destination.

5 Public transport in Hamburg

The Hamburg railway system consists of 68 stations and 6 metro lines. Although it is not the most complex public transport system in the world, it already has some kind of complexity making it hard to understand, in particular, if time-varying passenger data have to be explored in combination to the map. In this section, we will have a look into typical tasks that might be solved by travelers when using this map.

We will focus on a scenario where a family with three children plans a travel in Hamburg. This would mean that the trains should not be too crowded in order to safely travel with the family in a relaxed way. Since the family is free in choosing the dates between December 2016 and March 2017 for travel, they first have a look at the overview representation to figure out at what time periods there are not that many passengers.

For this reason, they look at the timeline histograms (see Fig. 8, bottom) for the number of passengers traveling in a certain month. It turns out that December 2016 is a good month to make such a journey since the other months during the available dates indicate many more passengers. The only better month would be March 2017, but in this month the family has other obligations and cannot travel.

Looking at the calendar-based visualization (Fig. 8, right side in the center), it can be observed that in the selected month (December 2016), the weekends (Saturday and Sunday) seem to be good dates since the number of passengers seems to be much less than over the week days which can be seen by the less red visual patterns in the calendar-based visualization. This gives the family the impression to plan their journey on a weekend in December. There are many more insights about the Hamburg public transport system once we start interacting with the visually enhanced metro maps, too many to explain all in this application scenario. For example, we might change the parameters to see the differences between people entering or leaving the trains or we might look at average values or variances in the values.

Once arrived in Hamburg, it is up to the family when to travel during the day, but they decided to travel early in the morning due to the fact that they have kids and their travel times cannot be freely chosen. Looking at Fig. 8 indicates that traveling in the morning is much better compared to the afternoon. This can again be seen in the calendar-based visualization.

Finding special attractions or doing sightseeing over the weekend is better on Sundays since on Saturdays the public transport is much more crowded than on Sundays. Hence, the family decides to do most of their sightseeing tours on Sunday (see Fig. 8).

Looking for interesting routes is also challenging, in particular if the chosen routes and trains should not be too crowded. This should typically be avoided for interchange stations. Looking at the maps for the selected time period (Fig. 9) the stations “Hamburg Hbf” and “Hamburg Altona” should be avoided because the station-aligned bubbles indicate many passengers, even for the weekend.

Figure 9 shows a calendar-based visualization for the Monday after the weekend. It seems that it is not a good idea to travel home in the morning since on Mondays there is typically rush hour in the morning; hence, the family decides to travel home after lunch.

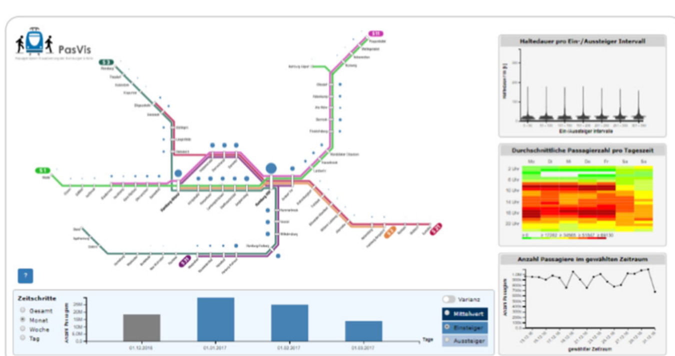


Fig. 8 The metro map of Hamburg with attached passenger data as well as extra views on the time-dependent number of passengers

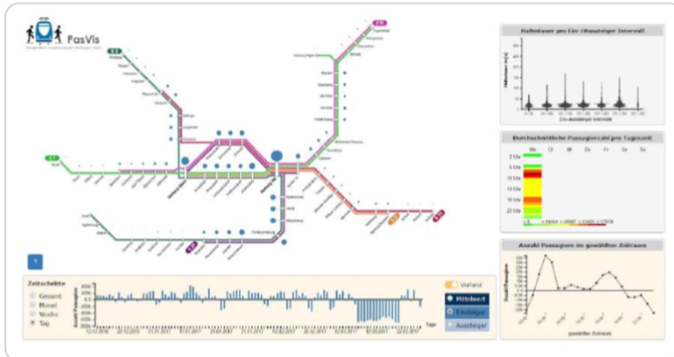


Fig. 9 Changing the temporal granularity as well as modifying several parameters gives additional insights into the passenger numbers. The views are linked and changing one aspect has the impact of also adapting other views simultaneously

6 User evaluation

We invited 20 participants to investigate if the enhanced public transport maps have any benefits compared to the original public transport maps without visual enhancements. To reach this goal, we first come up with a list of research questions and then as a second step we ask specific tasks to test those research questions. The independent variables in our user study are 'map without visual enhancement' and 'map with visual enhancement'. The dependent variables are accuracies and completion times, whereas the accuracies mean that the task could be solved in a meaningful way in a reasonable time. It may be noted that the user evaluation only focuses on the visual map enhancements without explicitly taking into account the algorithmic route computation as described in Sect. 4.

6.1 Research questions

Actually, we have designed and implemented the visually enhanced metro maps to provide benefits for the travelers, i.e., people trying to find an optimal way between two stations based on their personal preferences. Hence, our research questions are in favor of the enhanced maps and typically involve route finding tasks as well as judging time periods:

- *Research Question 1 (Comparison to original maps)* The map enhancements have NOT a bad impact on route finding tasks. This might be the case since every visual element in a map can be the cause of additional visual clutter and hence, difficulties to read and understand the visual representations.
- *Research Question 2 (Identification of time periods)* The map enhancements help to identify time periods (months, weeks, days) with a low number of passengers, and hence, this information would improve the traveling between certain stations represented in the public transport map.
- *Research Question 3 (Identification of routes* The map enhancements help to plan routes with a low number of passengers, for example avoiding crowded interchange points which could be beneficial to have faster travel times or to travel in a more relaxed way.

6.2 Study design

For answering the first research question (RQ1), we conducted a between-subjects study design, i.e., we showed 10 participants the original metro map and the other ten people were shown the visually enhanced map. Since the other two research questions (RQ2 and RQ3) are based on the enhanced maps, we showed all of them to the 20 study participants.

Before conducting the study, we asked the study participants to fill out a questionnaire about typical personal details. In this form, we also asked them to mention in which cities they have traveled to avoid possible prior knowledge when using the metro map. Finally, we provided a textual description of the user study, the stimuli, and the procedure of the experiment.

We kept the metro map the same but varied the start and destination stations for which the participants had to find a route. This serves as an independent variable in the study to judge if the visual enhancements might have a negative impact on the completion times or the correctness of the found routes. Each participant was shown 10 different start and destination stations, one after the other, and clearly highlighted to avoid searching tasks (similarly to the study by Netzel et al. 2017b).

For answering research questions 2 and 3, we let the 20 participants interact with the given map and either asked them to identify good time periods to travel (with a low number of passengers) for a given route or we asked them to identify a route for which they find a low number of passengers. For answering research question 2, we asked 10 trials for each participant; for answering research question 3 we gave the participants a time interval and just asked for identifying routes with a low number of passengers. The difference between research questions 2 and 3 is that in the first case we fix the route and ask for a time period, while in the second case we fix the time period and ask for a suitable route with a low number of passengers.

6.3 Stimuli and tasks

For the stimuli, we used our manually generated interactive metro maps (see Fig. 2b for an example) and highlighted start and destination stations in a way that they can be found preattentively (Healey and Enns 2012; Ware 2008), i.e., without ending up in a long-duration search task.

The two tasks to answer were either based on finding routes and telling the station names that lie on the found route in the traveling order or based on identifying a time period with a low number of passengers.

6.4 Pilot study and setup

We also conducted a pilot experiment with 2 participants who were excluded from the 'real' user study. Those 2 participants had to answer the 2 tasks for the 3 scenarios helping us to find answers to the given research questions.

In the pilot experiment, we asked for 20 trials of each task, but as a result we decided to reduce the number of trials to 10 for answering research questions 1 and 2 and only 1 for answering research question 3.

The study was conducted in an office that was isolated from outside distractions, artificially illuminated, and only a few number of objects were placed in the room to avoid paying attention to other things than to the stimuli. The computer monitor had a resolution of 1920×1200 pixels, while the participants sat on a chair with their eyes at the same height as the monitor and at an approximate distance of 50 to 80 centimeters from the monitor. We did not accurately measure those parameters but let the study participants feel comfortable.

6.5 Participants

We conducted a between-subjects study design for the first research question by splitting the 20 participants into two groups of ten each. Research questions 2 and 3 were investigated by a within-subjects study design in which each participant got 10 trials for the first part and just one trial for the second part.

All the 20 participants came from Western countries with a left-to-right reading behavior. The average age of the participants was 22.3 years, while the youngest participant was 16 and the oldest one was 51. The participants were non-experts in information visualization that we checked by showing them figures from traditional diagrams in information visualization like treemaps, node-link diagrams, or parallel coordinates plots. They had to name those diagram types, and as a second stage they had to explain the visualizations in a few words in a written form. Nobody of our non-experts in visualization was really able to name or explain those diagrams. However, they mentioned that they have seen metro maps before, but nobody ever traveled in Hamburg which was checked by requesting the prior knowledge of the participants.

All of our participants had normal or corrected-to-normal color vision which was confirmed by an Ishihara test or Snellen chart. Six participants wore glasses and 2 contact lenses. For taking part in the user study, we offered them some cookies. The individual experiments lasted for 23–35 min, while the two experiments in the pilot study took much longer, 60 and 67 min which made us rethink the study design and reduce the number of trials.

6.6 Study procedure

We invited the participants to an office isolated from outside noise and tried to reduce the number of distracting objects. The participants first received a questionnaire that was just used to ask personal information like gender, age, prior knowledge in visualization and the like.

Then they were shown public transport maps as they could be found in the interactive visualization tool. A 3-page-tutorial explained how to read and interpret the maps and which symbols and visual variables were used. After the participants confirmed they have understood the maps and the extra visuals in the maps, we asked them 3 test questions related to the tasks and stimuli they will see in the 'real' user experiment. Then the participants got some extra time to interact with the metro map tool and to test the scenarios given in the tutorial.

All of the shown stimuli and tasks in the test experiment will not be used in the 'real' experiment to avoid learning effects. In the real experiments, an operator was present in the room to take the time and write down remarks about the participants.

The real user study consisted of three separate parts, each testing one of the research questions, while for the first part the participants were split into two groups. This splitting was done randomly and not on any preferences based on the personal details. In the parts with the ten trials, we permuted the trials to avoid learning and fatigue effects. Between each part, there was a short break of a few minutes, while the duration was decided by the participant. There was also a give-up possibility but nobody made use of it. We did not limit the time for the single experiments, but nobody was really an outlier in terms of taking too much time compared to the others. When the participants were ready with one experiment, i.e., when they were sure they found a good solution, they should clearly state that in a way that the operator was well informed and could write down some remarks.

After the user study, each participant could give some final remarks that were recorded by the operator.

6.7 Results

In this section, we present the outcome of the user study focusing on the formerly asked research questions concerning comparisons between the original and visually enhanced maps, the identification of time periods when the route is given, and the identification of routes when the time period is given.

6.7.1 Original versus visually enhanced

Research question 1 was asking about the impact that the visually enhanced maps have compared to the original maps. To get any kind of valuable claim for this, we measured the completion times for each of the 10 participants and for each of the trials. In each trial, a different route was shown, while the same routes were shown for both, the original maps and the visually enhanced maps but in a permuted order to avoid learning or fatigue effects.

Participant group A that completed the task for the original maps took 387.7 s in average to answer all 10 trials. All of the found routes were correct which was checked by us after the experiments. Participant group B that completed the same task for the visually enhanced maps took 398.4 s in average to answer all 10 trials. Also those routes were correct solutions.

The very similar average numbers of the completion times for the original maps and the visually enhanced maps show us that the extra visual features have no large impact on the readability of the maps.

6.7.2 Identification of time periods

Research question 2 was asking about identifying a time period with a low number of passengers when a certain route was given. For finding a solution to this question, the participants had to interact with the visually enhanced public transport maps which took much more time than just finding a route like the task for answering research question 1.

For this task, we had all the 20 participants because this was not a comparison task, i.e., there were no learning effects between two scenarios. However, the routes for the 10 trials were permuted.

In total, it took 917.8 s for the 10 trials in average, i.e. more than one-and-a-half minutes in average to come up with a good time period for traveling on a given route in a public transport map. It seems that the interaction task takes much longer than the map reading task in a static map as in research question 1.

However, such a task might also be solved at home before planning a journey to a city due to the fact that the travel times should be fixed prior to the departure in the city.

6.7.3 Identification of routes

Research question 3 was asking about finding a good route with respect to a low number of passengers. To find an answer to this, we selected a time period and requested a route from the shown map.

This experiment was only done once to reduce the total amount of time the entire user study takes. As a final result, the participants could solve this task in 25.4 s in average. It is surprising that they were much faster than in research question 1 when just finding a route between a given start and a destination station. For research question 3, they had to check the entire map to locate a good route.

However, although the user study could be extended a lot by involving more parameter variations (independent variables), we are already confident with the results since they show that the interactively enhanced maps can be understood and used by non-experts in information visualization.

6.7.4 Participant feedback

In general, the participants liked the user study, but some of them gave useful remarks on how to improve the study, the maps, or even test the tool on other devices.

For example, one participant asked for the same study on a touch device because she thinks that it is unrealistic to use mouse interaction in a metro station. But for planning a journey at home such an interactive metro map setup with mouse interaction on a computer monitor might be good enough.

Some participants felt that they should have had more training before working with the interactions. They had the impression that there were too many details already and they did not use all the provided extras in the map to find the solution to a given task. However, this is not a big issue since we only checked a few scenarios but many more we could think of, consequently many more features must be used.

6.8 Comparison to existing systems

Apart from taking into account user tasks that particularly focus on visual map enhancements, we might evaluate or discuss the novel automatic and algorithmic route finding approach. However, in the current version of this article, we only evaluated the visual enhancements and omit the algorithmic navigation part, but instead, we provide a comparative discussion with existing systems from this domain.

There are several approaches that take into account interactive requests and navigation tasks of travelers to enhance the way how public transport systems can be used. For example, Rehrl et al. (2007) investigated tasks on smartphones for traveling aids; however, they do not include route finding tasks with specific information. Also Peischl et al. (2012) explored improved navigation in public transport systems without including further data sources to refine the route selection process. Searching for routes by using mobile devices was in focus of research by Salcedo and Battistutti (2014); however, they only focused on the public

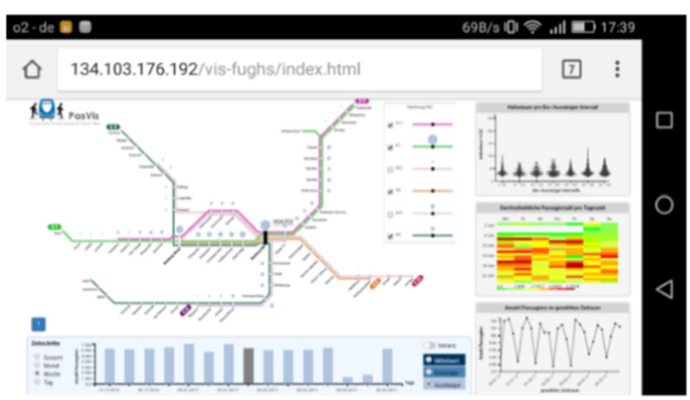


Fig. 10 The visually enhanced maps also run on a smart phone although we have not evaluated them in a user experiment. However, the touch interaction might be problematic for selecting tiny visual objects, this is much better on a larger monitor, maybe placed on a metro station's wall

transport system of Mexico City. Siddiqui et al. (2017) even included smart watches into the public transport navigation task, allowing real-time navigation which is not included in our navigation system. Moder et al. (2018) did not focus on the route finding task but more on helping visually impaired people to navigate inside the public transport which would be an add-on feature for our navigation system for future perspectives.

7 Limitations and scalability

Although we designed an interactive enhanced public transport map that has been shown to be useful and understandable with several benefits compared to the original not enhanced public transport map we are aware of the fact that it still suffers from lots of limitations, most of them concerning scalability issues focusing on data, algorithms, visualizations, perception, or users and interactions.

7.1 Data and algorithmic scalability

The first problem might come from the data itself. The German train service regularly uses counting trailers to estimate the number of passengers between line segments, i.e., between two stations. Also the number of entering and leaving passengers are counted. However, this data is not totally reliable because the counting trailers are not used for every trip at every time. Hence, there is also some kind of uncertainty in the data which is not taken into account in our current visualization.

Also algorithmic issues might occur when transforming the data into different perspectives given by the fact that users can request the data interactively based on their personal preferences. Also aggregating the data, for example temporally, costs some algorithmic effort, although much of this information can be preprocessed and stored until it is requested.

7.2 Visual scalability

The user is not able to adapt the design of the metro map, for example the layout of the lines and the stations. This can be problematic if extra visual variables must be added to enhance the metro map. In some cases, it would be good to adapt the map layout on the users' preferences, but that would make the implementation of the tool much more complicated.

Another problem concerning visual scalability is the fact that a map might be complex consisting of several hundred stations, possibly with labels. In such a scenario, it is pretty difficult to add extra visual information in a way to keep the map readable and to provide more information on the passenger behavior at the same time.

7.3 Perceptual scalability

From a perceptual point of view, it might become difficult to select very small elements, for example the bubbles aligned with the stations in the enhanced metro maps. Clicking on pixel-sized objects is pretty difficult, meaning we need another selection mechanism for that. This effect becomes much more challenging if we have to deal with smart phones and the selection interaction is done by touch where small or tiny visual objects are hidden by the finger for example. Also the different users with their personal issues might find interactions more or less useful for certain devices like tablets or mobile devices, in particular, if tiny visual objects have to be interacted with. However, interactions for zooming and visually enlarging those visual objects might be an option.

Moreover, the color coding is always problematic if we have to deal with visual variables (Ware 2004, 2008) like they occur in the metro maps. The lines, stations, interchange points, visual enhancements all might have different color, leading to misinterpretations for the users. Changing the color coding of metro lines is a bad design choice since normally they follow a mental map preservation concept, i.e., once the colors of the lines are learned they should stay the same all the time. However, some maps appear in various color codings making it hard to interpret them on the same visual characteristics although they encode the same public transport system. The use of various color codings and visual effects for stations and metro lines may mislead the users.

7.4 User and interaction scalability

The scenario of reading and exploring a public transport map is definitely limited to a certain number of people. For example, standing in front of a large touch monitor or even a smaller display, several people at the same time can already hide important information and on the other hand it is pretty difficult to interact 'collaboratively' when planning a journey in a city by using the same metro map. However, using different smart phones (see Fig. 10) might be a good solution to the negative effect that the final result has to be found by merging the opinions of several people together. In this way, we might speak here of user or interaction scalability.

Another challenging problem is definitely the level of expertise of the travelers. Although the maps are typically designed for non-experts in visualization, also those non-experts might have a different understanding or strength of interpretability of the visual variables encoded in the maps as well as the interactions to be applied to modify the views and the parameters.

7.5 Adaptability to other scenarios

It is pretty difficult to make all public transport maps in the world interactively enhanced by additional visual features. Our maps are manually designed, and it took a lot of effort to produce the maps first and then attach the extra data to it. Moreover, it is not guaranteed that all public transport systems provide such extra data.

Typically, the maps are only focusing on the metro lines in their simplest form. But it would be beneficial if also other transport options could be added, e.g., bus lines. This might again have the negative effect that the maps get visually cluttered.

Also the maintainability of the tool is a time-consuming process since public transport systems are not static, but they are dynamically changing from time to time. This demands for extending the displayed maps and services in an up-to-date manner. We do not say that it is impossible to maintain the public transport maps. We are collaborating with an expert transport map designer (Robin Woods from Communicarta Ltd.) who can give useful insights about modifications in a transport system of cities from all over the world. Hence, the maintenance has to focus on two aspects, the visual representation of the map as well as the multi-network model for guaranteeing an up-to-date route finding algorithm.

8 Conclusion and future work

In this paper, we described a public transport visualization with interactive visual enhancements for taking into account the passenger numbers, extended to a public transport navigation system. The passenger data can be aligned with the stations as well as with the metro lines; moreover, additional timeline-based histogram views or calendar-based diagrams can be requested to get an overview about the dynamic passenger behavior on different levels of temporal granularity. Further support is given by algorithmic analyses trying to identify user-specified routes. We discussed interactions and illustrated the usefulness of the visualization in an application scenario for the public transport map of Hamburg in Germany. Finally, we discussed limitations and scalability issues and described the design and results of a user evaluation. For future work, we plan to add more interaction techniques as well as extra data sources containing the train travel times and ticket prices to provide an overview about the travel costs. Also an eye tracking experiment (Kurzhals et al. 2014, 2017) with travelers under real conditions might be a good idea to investigate if the interactive metro maps are really useful enhancements compared to the original static maps.

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