Detecting Green Roads by using Open Routes

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ABSTRACT: *The roads which are characterized by green effect are preferred by both pedestrians as well as by vehicle drivers. Using openrouteservice, we have evaluated the green routes and find the extent of greenery in these roads. With the help of OpenStreetMap, we have measured the greenness in the roads for which we used imagery and three dimensional data. . We studied the impact both at the level of the individual route and at the urban level for then cities. For individual routes, we find how strongly green routes differ from the respective fast routes. Besides, we measured the parts of the road network which represent important green corridors as well as unattractive parts which can or cannot be avoided at the cost of reasonable detours. During analysis we found that the significance of green spaces for the provision of attractive green routes and provide new insights for urban planning.*

Keywords: Routing, Openstreetmap, Route Choice, Urban Vegetation, Sustainable Mobility

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1. Introduction

Route preferences of pedestrians and cyclists differ from the ones of car drivers. In addition to distance and time effort, aspects such as slope, safety, aesthetics, presence of green areas, accessibility to locations of interest, avoidance of noise and air pollution, road surface and heat stress play a role [1, 30, 33, 34, 35, 38]. Several of these factors have been integrated as routing weights in specialized navigation systems [41, 26, 34, 23]. We focus here on green routes – i.e. routes with a high share of vegetation alongside of them. Urban green spaces have been shown to clearly benefit mental and physical well-being of city dwellers [37, 15, 12, 20, 18] in addition to providing other important ecosystem services [8] and space for recreational and cultural activities such as sports, experiencing nature or social exchange [5, 16, 31]. These effects are not limited to public green spaces such as parks but also include urban greenery along roads and paths.

Including additional factors such as greenness in the route generation process will in most situations increase the travel distance and time, which in many situations is still the most important factor in route choice. Therefore, it is necessary for the design of navigation apps and planning support systems to study these trade-offs and to adjust weighting factors so that reasonable and attractive route recommendations are generated.

Previous studies have analyzed different routing options for pedestrians and cyclists based on different factors such as cycling infrastructure, traffic volume or scenery [13, 21]. Novack et al [23] has analyzed one thousand randomly chosen routes with respect to detour factors with respect to green, noise-avoiding and social routes for pedestrians at the example of the city of Heidelberg. We extend this work here with respect to the following aspects: i) we analyze routes for two cities – Heidelberg and Dresden –, ii) we generate a larger set of routes that connect different quarters of the cities and iii) we analyze detour factors both for pedestrians as well as for cyclists. In addition to the evaluation from the perspective of the individual user ("what is the best route from A to B?") we also analyze the routes from the perspective of city planners to identify parts of the traffic network where attractive, green routes exist and where they are missing.

The aims of the analysis at the example of the two cities are twofold:

1. How do the green routes differ from the respective fast routes? (RQ1)

2. Which parts of the citywide traffic network represent important, green corridors, which parts can be potentially avoided due to low greenness and which parts cannot be avoided since no green alternatives exist? (RQ2) We aim at a systematic analysis of the effects of greenness on the individual routes and a quantification of the availability of green routes for cyclists and pedestrians in both cities.

2. Methods and Data

2.1 Study Sites

The analysis was performed in two German cities: Heidelberg and Dresden. Dresden is the capital of the federal state of Saxony and is located in the eastern part of Germany with a population of 563,011 (2019) and a total area of 328.8 km^2. Heidelberg is smaller in size (108,8 km^2) and population (160,355 in 2019). Both cities are traversed by large rivers - the Elbe in Dresden and the Neckar in Heidelberg - which puts constraints on the connectivity between several city quarters. Restrictions also arise due to the terrain, especially in the case of Heidelberg where the low mountain range Odenwald reaches into the city limits. Both cities provide extended green spaces such as municipal parks, floodplains along the rivers, large forest areas at the city borders and private gardens within residential areas. An estimated 74% of Heidelberg and 66% of Dresden are covered by vegetation based on land cover map by DLR (2020) [7]. As most German cities, cycling infrastructure is present and cycling is encouraged by the city administration.

2.2 Methods

2.2.1 OSM Data Quality Assessment

OpenStreetMap (OSM) was used as the data source for the road network, the cycling infrastructure and partly for the identification of urban vegetation. Its benefits are its open licence and its increasing availability all over the world. Since OSM data is produced by local and remote volunteers, the data quality varies spatially and depending on the thematic domain. Therefore, it is important to check data quality before using it in scientific analyses and other applications. We followed an intrinsic data quality approach [32, 4, 2] and queried contributions for different *highway* categories and *cycleway*s and studied the development of contributions over time. OSM history was accessed via the ohsome API that builds on the OpenStreetMap History Database (OSHDB) [28]. We analyzed the temporal evolution of the overall length of all OSM objects belonging to relevant *highway* classes. In addition, we analyzed the number of OSM users in Heidelberg and Dresden that contributed actively in the domain of roads and paths (*highway=**). The analysis of the data quality was performed in

R [27] using the packages sf [25], RCurl [36], geojsonio [3], tidyverse [40], ggplot2 [39] and ggpubr [14].

2.2.2 General Routing

The pedestrian and bike routes were calculated using the openrouteservice (ORS), an open source routing engine which is based on OSM data [22]. Its source code is publicly available on Github (https://github.com/GIScience/openrouteservice) and it can be used for worldwide routing queries through its public API or web client (https://maps.openrouteservice.org). The routing function of the ORS provides different user profiles such as car, bike or pedestrian as well as other query parameters (e.g. avoid ferries) to adapt the route to different user preferences. By integrating additional data in the route calculation, the ORS can generate specialized routes such as green routes, which prefer paths along greenery, or quiet routes, which prefer paths with less traffic noise. For this study, a new instance of the ORS was created which uses region specific data for the greenness of streets and uses a different weighting function to balance greenness, steepness and duration of the route.

In general, routing algorithms are based on an undirected graph consisting of edges representing streets or paths and nodes representing intersections. Every edge in the graph is assigned a weight, e.g. the street length to find the shortest route or the travel time to find the fastest route. Since the travel speeds and preferences of pedestrians and cyclists are different, separate graphs are built for each of them. The optimal route between two points, e.g. the fastest or shortest, is the route with the lowest overall weight. There are different algorithms to find this optimal route such as the Dijkstra's algorithm [6], which is also offered by the ORS but other, more efficient algorithms are preferred. In this study, the route calculation was based on the A* algorithm [10].

The default route recommended by the ORS is the fastest route with some restrictions based on the street types to make the route more attractive, e.g. avoiding unpaved paths for cyclists or considering the fact that cyclists may need to dismount their bikes and walk on designated foot paths. In the remainder of the text we refer to this route as the fast route. The same restrictions on street or path types were considered in all our simulations - i.e. also for the green routes.

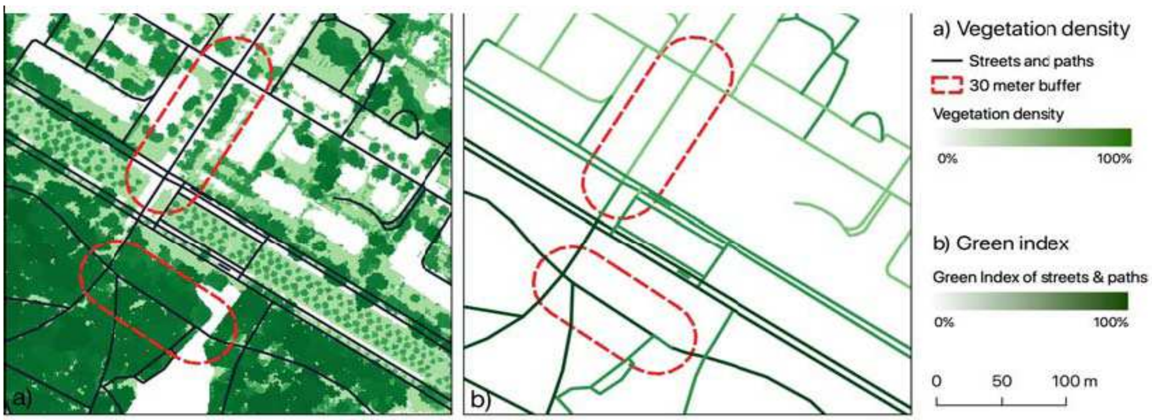

Figure 1. Calculation of the green index at the example of a subset in Dresden where the estimation was based on vegetation density data derived from 3D laser scan data. The green index is the share of vegetation in a 30m buffer around each street segment

2.2.3. Green Routing

Conventional routing algorithms only use the distance or travel time of the route segments as weights in the routing graph to find the optimal route. In order to calculate a green route, these weights have to be adapted by integrating the greenness of each street segment into their calculation. This information is not given in OSM directly but needs to be derived prior to building the routing graph. Since data availability differed in Dresden and Heidelberg, two different approaches were used. In Dresden, data on vegetation density with a spatial resolution of 1 meter derived from 3D laser scan data was used [11]. In Heidelberg, the vegetation presence was quantified by combining OSM data, Sentinel-2 imagery and municipal tree cadastre data. Information from OSM and Sentinel-2 data were fused using the Dempster-Shafer Theory as described in Ludwig et al. [19] to yield a map of vegetation presence which was later enriched by single trees extracted from OSM and in the municipal tree cadastre data. In the end, the greenness of a certain street segment - called green index from now on - was quantified by calculating the fraction of area covered by vegetation with a 30 meter buffer around the street segment (c.f. Figure 1).

Performing a visibility analysis to only consider vegetation which is visible from the street and not obscured by buildings was tested but had to be excluded eventually due to the high computational costs.

For the green routing, the weights of the edges in the routing graph were calculated using

$$w_i = d_i + \frac{((1 - g_i) * w_g + s_i)}{2} * d_i \tag{1}$$

where w_i is the weight of street segment i, d_i is the time needed to traverse it, g_i is its green index, s_i is its steepness index and w_g is the green weight factor with range [0,1], which controls the trade-off between greenness and duration of the route. The higher this green weight factor, the greener but also the longer the route. The green index was converted to a cost factor using 1 - g_i, so that streets with low greenness have higher weights and are thus avoided. Since the green index and steepness index represent intensities, it was multiplied by the travel duration of the respective route segment to yield an exposure value.

The steepness was included as an additional cost factor in the function to avoid yielding routes with high ascents and descents. This was done, because currently the ORS does not consider the slope in the calculation of the travel time, e.g., by assuming slower travel speeds for ascending route segments. The influence of the steepness is defined by the *steepness difficulty* parameter of the ORS which was set to 1 (*moderate*) in this study.

In this study, different green routes were compared to their respective fast routes. The fast routes did not consider greenness, i.e. their green weight factor was w_g = 0. Green routes were created using green weight factors ranging between 0.1 and 1 (0.1 <= w_g <= 1). The higher this value, the greener and longer the route. An example of a fast (w_g = 0) and a green route (*wg* = 1) for pedestrians is given in figure 2. While the fast route (22:50 minutes, 1.9 km) in the example follows the main road through a built up area, the green route (26:20 minutes, 2.2 km) leads through natural and agricultural fields. The green route was 15% longer (3:30 minutes) but its greenness value was almost three times higher (260%) compared to the fast route.

Figure 2. Example of a fast and green pedestrian route in Heidelberg. The green route (26:20 minutes, 2.2 km) is 15% longer (3:30 min) than the fast route (22:50 minutes, 1.9 km) but it's green value is almost three times higher (260%) compared to the fast route

2.2.4 Route Simulations

To answer the research questions, random trips for pedestrians and cyclists were simulated for Heidelberg and Dresden by generating random start and end points within the respective administrative boundaries. To simulate the trips according to the distribution of the population density the trips were generated based on the city districts with each trip starting in one district and ending in another one. In addition, short trips were simulated by generating random start and end points within the same district. In this way, more routes were generated in the populated city center and less routes in the unpopulated outskirts (e.g. forests). For pedestrian routes, the minimum length was set to 200 meters and the maximum length to 5 kilometers to represent both short trips of everyday life (e.g. grocery shopping) as well as longer recreational trips (e.g. taking a walk, touristic walking tours). The minimum and maximum lengths of cycling trips were set to 500 meters and 15 kilometers respectively.

In very rare cases the computed duration of the green route was lower than the fast route, since the terrain was only considered through the steepness index and not in the calculation of the route duration. This was for example the case when a green route lead through the forested low mountain range close to Heidelberg, while the fast route went around it yielding a longer route. This phenomenon was due to the fact that the very high greenness in the forest made up for the high steepness in the routing costs. Since such green alternative routes might not be seen as attractive alternatives in reality, they were dismissed and another random trip was generated.

Two separate simulation runs were performed to answer the two research questions. The first run was performed to compare the green routes to their respective fast routes in terms of duration and similarity (RQ1). For each city, 3000 trips by bike and 3000 trips by foot were simulated. For each trip, the fast route and 10 green routes with increasing green weight factor *wg* in the range of 0.1 to 1.0 were calculated.

A second simulation run was performed to analyze the street network connectivity in regard to the exposure of cyclists and pedestrians to greenness (RQ2). This analysis was performed in Dresden by simulating 8858 bike trips and in Heidelberg by simulating 9024 trips for pedestrians. For each trip, the fast route and an alternative green route with green weight factor *wg* = 1 were calculated and compared to each other. Avoidable street segments were identified by extracting the route segments of the fast route which were not identical with the green route. Preferable street segments were identified by extracting the route segments of the green route which were not identical with the fast route. Unavoidable route segments were defined as streets or paths which were contained in both the fast and green route and showed a green index lower than 0.1. Streets where the fast and green route were identical and which had a green index higher than 0.6 were considered as ideal route segments, i.e. the route is both fast and green. The extracted route segments were aggregated into heatmaps showing avoidable, preferable, unavoidable and ideal street or path segments. The heatmaps were created using the Kernel Density Estimation module of SAGA GIS version 2.3.2 (http://www.saga-gis.org/en/index.html). Since this tool requires point data as input, the extracted route segments were converted from line to point geometries with a distance of 5 meters between the points. The rest of the analysis was implemented using Python 3.9 (https://www.python.org/) and the openrouteservice Python package (https://pypi.org/project/openrouteservice/).

3. Results

3.1 OSM Data Quality Assessment

Most road classes in both Heidelberg and Dresden showed a contribution pattern that indicates saturation (c.f. figure 3) – together with the constantly high user activity (c.f. figure 4) in both cities this can be taken as an indicator for high completeness of the road network. Road categories that could be assumed to be highly complete in both cities consist of: *primary*, *secondary*, *tertiary*, *residential*, *unclassified* and *pedestrian* roads. In addition, the category *living_street* seemed saturated in Dresden, while in Heidelberg this was true for the category *track*s .

Two road categories were declining in both cities: *roads* and *cycleway*s. *Roads* are a category used if a road cannot be categorized clearly into one of the other tags so a decline of this category is both expected and an indication of increasing data quality. The category *cycleway* represents separate ways for cyclists. Cycleways that are not separated from a road are usually mapped with a *highway=** tag and the additional key *cycleway=** that specifies the type of the cycleway. The use of the tag *cycleway=** has evolved over time leading to a decrease in the use of *highway=cycleway*. The length of ways tagged as *cycleway* has increased in both cities over time which can be taken as an indication that cycleways are relatively complete (c.f. 5).

The road categories *path*, *service* and *footway* seemed not yet saturated. In Heidelberg in addition the category *living_street* and in Dresden *track* were not saturated. The different highway values are explained in the OSM Wiki (https://wiki.openstreetmap.org/wiki/Key:highway).

3.2 Route Duration vs. Route Greenness

As expected, the route simulations showed that the duration of the green route increased with an increasing green weight factor. Compared to the fast route, 95% of green cycling routes with *wg* = 1 were up to 21% longer in both cities. For

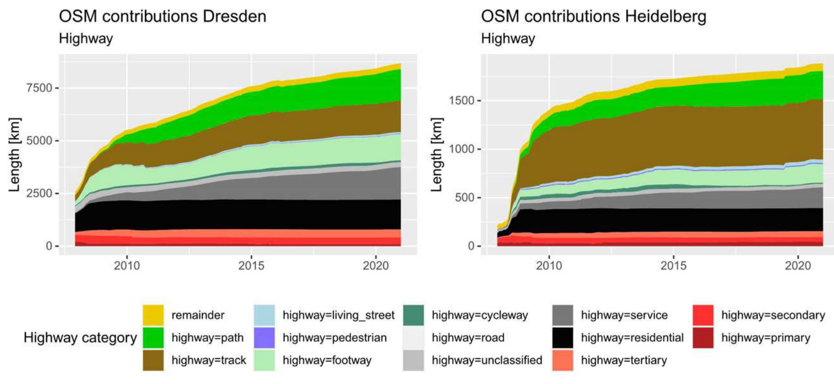

Figure 3. Development of highway contributions in OSM for the two case studies. The category remainder captures all remaining road classes

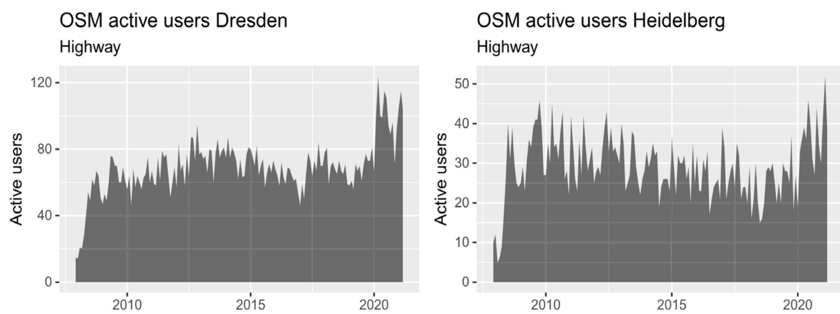

Figure 4. Active OSM users that contributed highway features for the two case studies

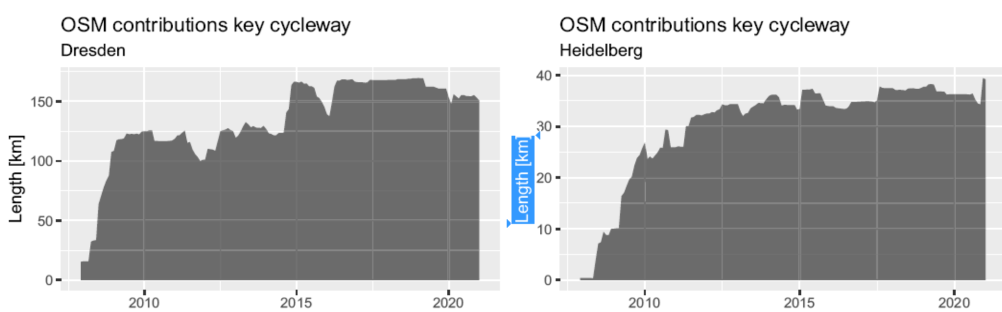

Figure 5. Development of cycleway contributions in OSM for the two case studies. The figure does not reflect that cycleways can be on one or both sides of the street but tagged on a single way

pedestrian routes, this value was at 16% in Dresden and 13% in Heidelberg. Since detours of this magnitude have also been reported in other studies which have analyzed the route choice behavior (e.g. [24]) these simulated greener alternative routes can be seen as reasonable. Green routes which showed a longer detour than this usually led through forested or agricultural areas bordering the outskirts of the cities, so there was a considerable gain in greenness justifying the bigger detour.

The increase in duration also depended on the overall length of the trip (Figure 6). For bike trips in Dresden which took up to 10 minutes, the green route was on average only 8 seconds (1.7%) longer than the fast one, while for trips which took 20-30 minutes the increase in travel time was about 1:32 minutes (6.1%). In both cities, the increase in duration of the green route was lower for pedestrian trips than for cycling trips, which might be due to the fact that the pedestrian routes are shorter leaving less options for detours.

For both pedestrian and cycling routes, the gain in greenness exceeded the increase in duration on a percentage basis. The gain in greenness relative to the increase in duration was at 3.39 for cycling routes in Dresden, i.e. for every 1% increase in duration the routes were 3.39% greener (Figure 7a). In Heidelberg, this value was even at 5.26% (Figure 7c), which is probably due to the fact that many green routes connecting the city center with districts in the eastern part of the city lead through the Odenwald forest. These alternative routes are often a lot greener but also steeper, which is why they cannot always be seen as valid alternatives in reality - at least if the purpose of the trip is not sporting activity. For pedestrians, the relative gain in greenness compared to trip duration was also slightly higher in Heidelberg than in Dresden (Figure 7b+d).

With an increasing green factor, the green route also deviated stronger from the fast route. These deviations were generally higher for cycling routes than for pedestrian routes (Figure 8). This might be due to the fact that cycling routes were on average longer than pedestrian routes giving them more options for alternative routes. The deviations were strongest for cyclists in Dresden where green routes with the highest green factor $w_g = 1$ were on average 51% identical with the fast route (Figure 8a). In Heidelberg, the fast and green cycling routes were more similar sharing on average 59% of the route (Figure 8c).

3.3. Analysis of the Road Network with regard to availability of Green Routing Alternatives

In Dresden the fast cycling routes mostly lead along the main streets, while the green alternative routes lead along the Elbe river or through public green spaces such as the Great Garden (in the south east of Figure 9). The later one seems to be a very valuable connection in the bike network, since it is both the fastest and greenest route to choose for many bike trips. Bridges across railways on the other hand often show low vegetation and cannot be avoided easily by making reasonable detours (marked in purple in Figure 9). Upgrading these street segments could increase the quality of the whole cycling network.

A comparison between the avoidable and preferable greener routes in Dresden and real cycling traffic data collected from

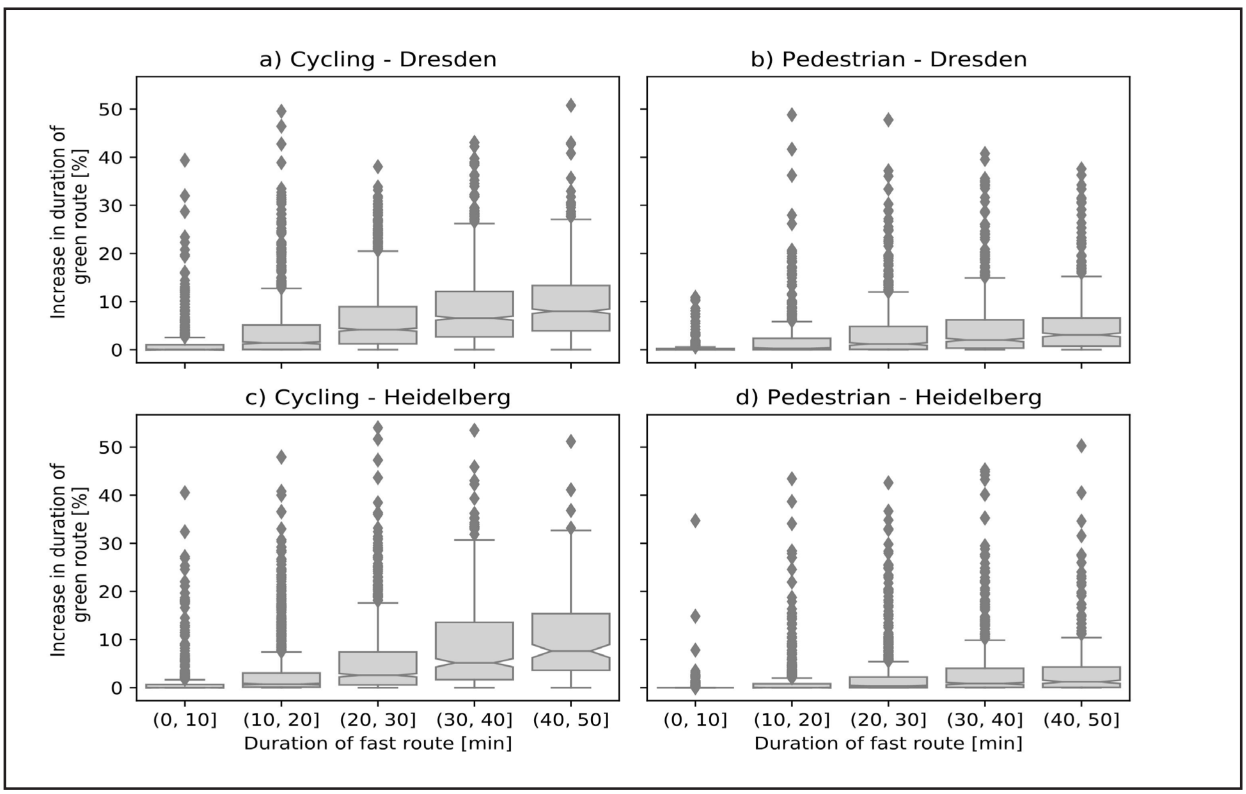

Figure 6. Increase in duration of green routes compared to fast routes depending on trip duration. Trips were grouped based on duration of the fast route in bins of 10 minute intervals

2018 until 2020 [9] indicated that the preferable greener cycling routes were also frequently used by cyclists in reality (Figure 10). For example, the cycling path along the Elbe river and through the Great Garden - which were identified as preferred segments in our analysis - showed high numbers of cyclists in reality. Still, some routes, which according to the simulated data could be avoided in favour of greener routes, were still quite highly frequented in reality, e.g. the main road leading from East to West in the lower part of Figure 10.

In Heidelberg, the avoidable and preferable paths were analyzed for pedestrians (Figure 11). The main roads leading through built-up areas were avoided while routes through green spaces and along agricultural fields were preferred by the green routes compared to the fast routes. The Ochsenkopfwiese for example, a public green space in the center of Heidelberg (Figure 11 center), was supposed to be replaced by a bus depot until the plans were stopped by a referendum. The results of this analysis confirm how important the preservation of this green space is, since it is one of several important green corridors that enable citizens to move through the city on attractive routes. Similar to Dresden, bridges and overpasses, such as the one close to the main train station cannot be avoided easily due to the lack of green alternative routes.

4. Discussion

The simulations have shown that in many cases it should be possible for both pedestrians and cyclists to take greener, more attractive routes by taking reasonable detours. Especially urban green spaces and paths along rivers represent important green corridors in cities which should be preserved. Bridges without any greenery on the other hand often form bottlenecks where no reasonable green alternatives exist. Enhancing greenness in these places by the city administration could increase satisfaction of cyclists and pedestrians and stimulate the use of sustainable traffic modes.

The validity of these results was supported by the comparison to real cycling traffic data in Dresden, which showed that most of the preferable green routes were also highly frequented in reality. However, the fact that some avoidable routes identified in our simulation were still frequently used in reality suggests that there are other factors in the route choice of cyclists which have not been considered in this study such as perceived safety or quality of the bike infrastructure. These aspects

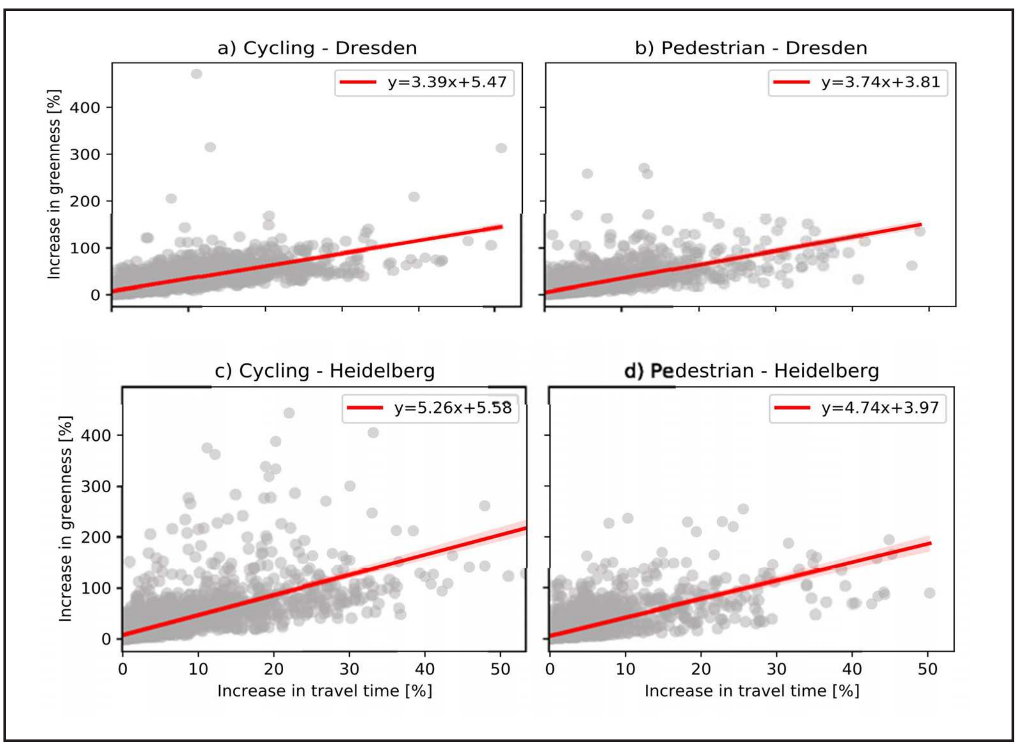

Figure 7. Increase in greenness compared to the increase in travel time of simulated green cycling (a+c) and pedestrian (b+d) routes in Heidelberg and Dresden. The red line is based on a linear model, shown together with the 95%-confidence band

should be investigated in future studies. In addition, other quality metrics such as the continuity of the route as described by [29] could be included in the comparison of the routes.

There are some improvements to the routing algorithm which should be considered in future studies. First, the terrain should be considered in the calculation of the route duration to make sure to generate attractive alternative routes without high ascents. Second, other stronger than in our case studies. Other factors of relevance are presumably the terrain, presence of routing algorithms such as evolutionary or k-shortest path algorithms should be evaluated for their potential to generate multiple pareto-optimal route options which might not be found using the A* or Dijkstra's algorithm.

Our two case studies represent two cycling friendly cities with relative large shares of private and public green. For cities with a different cycling infrastructure and green space distribution the trade-off between greenness and time effort might be large water bodies and the general layout of the cities which further influence which pathways are of special importance in regard to the connectivity of the network. Therefore, the results of this analysis might not be directly transferable to any other city.

Still, given a sufficient completeness of roads, footpaths and cycling infrastructure in OSM a transfer of our green routing approach to other cities seems feasible. As done in this study, an OSM data quality analysis should be conducted prior to the analysis. In addition, the transferability of the method depends on the available data used to estimate the greenness of the streets. High quality vegetation density data derived from 3D laser scan data as used in Dresden are usually not available for most cities. However, a comparison of green routes in Dresden based on i) OSM in combination with Sentinel-II data and ii) the use of vegetation density data from 3D laser scans showed very similar results indicating that free and open data are sufficient to generate reasonable green routes if high quality data is missing [17]. In this way, the proposed approach could also be used to assist urban planners in identifying potential for improvement in the road network for pedestrians and cyclists even if no local data on their mobility patterns are available.

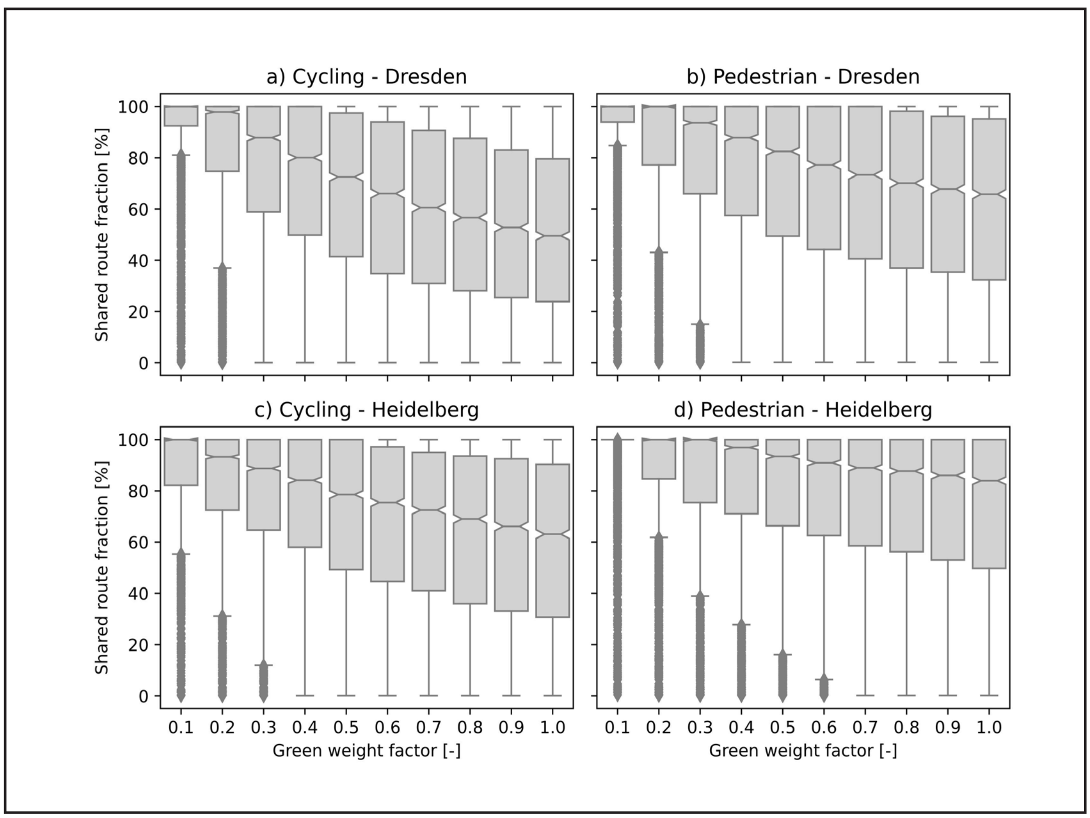

Figure 8. Shared fraction between fast and green route dependent on the green weight factor w_g. With increasing green weight factor, the green and fast routes diverge from one another

Figure 9. Avoidable and unavoidable route segments for cyclists in Dresden due to lower greenness (left). Preferable greener alternative routes and ideal route segments (right)

5. Conclusion

For our two case studies, reasonable green routing alternatives exist for cyclists and pedestrians for most parts of the cities highlighting the importance of urban green spaces. We were further able to identify bottlenecks in the road network which should be prioritized by urban planning to further foster sustainable and healthy traffic. A comparison with observed cycling data suggest both that the approach is generally suitable but that additional factors should be taken into account.

Figure 10. Comparison between our analysis (left) and observed cyclists (right) for Dresden. Greener alternative routes identified in the simulation are also highly frequented in reality

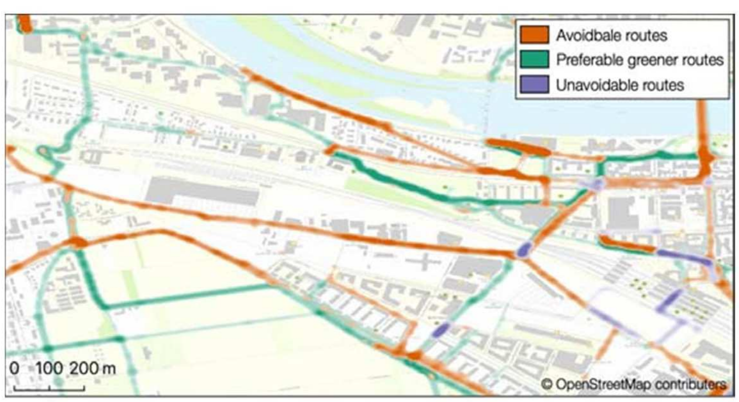

Figure 11. Unavoidable, avoidable and preferable greener alternative routes for pedestrians in Heidelberg. Green routes avoid the main roads leading through built up areas while preferring fields and urban green spaces

Given the importance of pedestrian and cyclist traffic with respect to climate change adaptation and public health further effort will be undertaken to scale the presented green routing with the public ORS instance to much larger regions. Upcoming work will also focus the extension of the green routing approach by incorporating further health related factors such as the avoidance of heat stress.

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