ECAI 2014
T. Schaub et al. (Eds.)

doi:10.3233/978-1-61499-419-0-1149

Bicycle Route Planning with Route Choice Preferences

Jan Hrncir and **Qing Song** and **Pavol Zilecky** and **Marcel Nemet** and **Michal Jakob**[1]

Abstract. Bicycle route planning is a challenging problem because of the diverse set of factors considered by cyclists in choosing their cycling routes. We provide a solution to this problem based on a formal model expressive enough to represent transport network features and cyclists' preferences grounded in the studies of real-world bicycle route choice behaviour. Our solution employs the A* algorithm together with vectors of cost and heuristic functions – able to optimise routes for travel time, comfort, quietness, and flatness. We have implemented, practically deployed and experimentally evaluated our solution in the challenging setting of the city of Prague. The experiments confirmed that the planner is able to return high-quality plans in less than 250 milliseconds per query.

1 Introduction

Utility cycling, i.e., using the bicycle as a mode of transport, is the original and the most common type of cycling in the world [7]. Utility cycling has a range of health, environmental, economical, and societal benefits [3] and has been promoted as a modern, sustainable mode of transport.

In contrast to car drivers, cyclists consider a significantly broader range of factors when deciding on their routes. By employing questionnaires and GPS tracking, it is now known [2, 15] that cyclists are sensitive to trip distance, turn frequency, slope, junction control, noise, pollution, scenery and traffic volumes. Moreover, the relative importance of these factors varies widely among cyclists and can also depend on the weather and the purpose of the journey.

Finding routes that properly take all the above factors into account is no easy task, particularly when cycling in complex urban environments. Consequently, cyclists can benefit from automated route planning software to help them discover routes that best suite their transport needs and preferences. Such planners would be particularly useful for inexperienced cyclists with limited knowledge of their surroundings but they would also benefit experienced riders who want to fine-tune their routes [4].

Bicycle route planning is a challenging AI problem because of the multiple route planning objectives and rich representations required to properly model transport network features and cyclists' needs and preferences. In contrast to car and public transport route planning, for which advanced algorithms and mature software implementations exist [1], bicycle route planning is a surprisingly underexplored topic. Although several bicycle route planning applications have recently emerged (see below), these follow adhoc approaches and provide very little information about their internal working.

In this paper, we aim to change this situation and provide a contribution that puts bicycle route planning firmly on the AI research agenda. To this end, we provide a formalisation of bicycle route planning which is general enough to consider cyclists' route choice preferences and a wide set of real-world transport network features. Compared to previous work, we show explicitly how the transport network features are used to compute the values of customisable criteria cost functions, which are itself based on recent studies of cyclists' route choice behaviour. We solve the problem by employing a scalarised multicriteria search, integrate the solution with real-world data and evaluate it in the realistic settings of the Prague city.

2 Related Work

From the practical implementation perspective, many online route planners have been developed in the past few years for cycling purposes. Google Maps[2] supports bicycle trip planning in some areas. However, it does not allow to set up any cycling preferences. OpenTripPlanner[3] is an open source multimodal trip planner. Bicycle planning is one of the modes of the OpenTripPlanner. It allows users to select a desired ratio of quickness to flatness to bike friendliness and it employs two different methods for routing: the A* algorithm and Contraction Hierarchies [5]. Cyclestreets[4] is an online cycle journey planner, employed in the UK. It allows users to enter an origin, a destination and an average cruising speed. The web application returns three routes: the fastest, the quietest and the balanced one. BBBike[5] is a cycle route planner originally developed for Berlin, Germany. It allows for a route selection based on multiple criteria: shortest route, road surface, street category, and avoidance of unlit streets.

Until now, there has been very little published within this field. In Robert et al. [14], the authors discuss the design of a web-based tool that helps cyclists to determine safe and efficient routes. In Su et al. [12], the authors developed a web-based cycling route planner for Metro Vancouver, Canada. It enables users to find a cycle route based on the selected preference, chosen from shortest path route, restricted maximum slope, least elevation gain, least traffic pollution and most vegetated route. Hochmair et al. [9] proposed a bicycle trip planner for Broward County, Florida that enables users to select among five criteria: fast, safe (least interaction with traffic), simple, attractive, and short. The criteria were decided based on observed route choice behaviour of cyclists [8]. Recently, Tal et al. [13] proposed an energy-efficient weather-aware route planner for electric bicycles.

3 Problem Formalisation

In this section, we describe the mathematical model of cycleway network and its associated parameters. Based on our new model, we give a formal definition of the cycle planning problem.

[1] Agent Technology Center, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic, emails: {hrncir|song|zilecky|jakob}@agents.fel.cvut.cz, nemetma1@fel.cvut.cz.

[2] http://maps.google.com/
[3] http://opentripplanner.com/
[4] http://www.cyclestreets.net/
[5] http://www.bbbike.org/

3.1 Cycleway Graph

The cycleway network is represented by a directed weighted *cycleway graph* $G = (V, E, g, h, l, f, F, \overrightarrow{r})$, where V is the set of nodes representing start and end points (e.g., cycleway junctions) of cycleway segments, and $E = \{(u,v)|(u,v \in V) \wedge (u \neq v)\}$ is the set of directed edges representing cycleway segments. The cycleway graph is directed due to the fact that some cycleway segments in the map are one-way only. The function $g : V \to \mathbb{R}^2$ assigns a latitude and a longitude values to each node $v \in V$; an altitude value is assigned to each node by the function $h : V \to \mathbb{R}$. The horizontal length of each edge $(u,v) \in E$ is given by the function $l : E \to \mathbb{R}_0^+$.

For each edge $(u,v) \in E$, the function $f : E \to \wp(F)$ returns the *features* associated with the edge reflecting certain properties from the map data (e.g., a surface of a cycleway segment, a road type). The set of all features of edges is denoted by F. Note that an edge can have multiple features assigned to it, thus $f((u,v)) \subseteq \wp(F)$ with the number of elements $|f((u,v))| \geq 1$. We propose a k-criteria description of the problem. For each edge $(u,v) \in E$ we define a k-dimensional vector of criteria base values $\overrightarrow{r} = (r_1, r_2, \ldots, r_k)$. Criterion base value $r_i : E \times \wp(F) \to \mathbb{R}_0^+$ for an edge (u,v) reflects an integrated influence of map features $f((u,v))$ with respect to criteria i. For example, the features indicating that the edge is a residential street with bad surface quality will have a negative influence on the speed of cyclists when travel time is considered as a criterion.

3.2 Cost Functions Definition

We consider a multicriteria cost function for each edge represented as a k-dimensional vector of criteria $\overrightarrow{c} = (c_1, c_2, \ldots, c_k)$. The value of any criterion $i \in \{1, 2, \ldots, k\}$ for the given edge $(u,v) \in E$ is computed by the cost function $c_i : E \times \wp(F) \to \mathbb{R}_0^+$. A criteria cost function c_i is defined using a criteria base value r_i.

In this paper, based on the surveys of cyclists' route choice [2, 15], $k = 4$ criteria are defined to meet different requirements of cyclists[6], namely the travel time c_{tt}, comfort c_{co}, quietness c_{qu}, and flatness c_{fl}. The cost functions induce a cost vector marked by $\overrightarrow{c} = (c_{\mathrm{tt}}, c_{\mathrm{co}}, c_{\mathrm{qu}}, c_{\mathrm{fl}})$. The related criteria base values are marked by $\overrightarrow{r} = (r_{\mathrm{tt}}, r_{\mathrm{co}}, r_{\mathrm{qu}}, r_{\mathrm{fl}})$. An important aspect is uphill and downhill. Next, we detail how these are accounted for and define the cost functions.

When riding a bicycle, changes in elevation affect the cyclist's velocity and hence affect the criteria cost functions. Going uphill reduces speed and require additional cyclist's energy expenditure. On the other hand, riding downhill usually means a speed-up, the possibility to stop pedalling and rest.

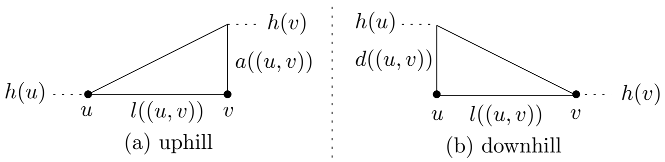

Figure 1. (a) Positive vertical ascend a (b) Positive vertical descend d

For the case of uphill rides, a positive vertical ascend $a : E \to \mathbb{R}_0^+$ (cf. Figure 1) and a positive ascend grade $a' : E \to \mathbb{R}_0^+$ are defined for the given edge $(u,v) \in E$ as following:

$$a((u,v)) := \begin{cases} h(v) - h(u) & \text{if } h(v) > h(u) \\ 0 & \text{otherwise} \end{cases}$$

$$a'((u,v)) := \frac{a((u,v))}{l((u,v))}$$

Then we use a modification of Naismith's rule [11]. The Naismith's rule for hiking or walking suggests that a person needs 1 hour to walk 5 km on a flat surface plus one hour for every 600 meters of ascend. That means that one meter of positive vertical ascend a can be replaced by $a_l = 8$ meters distance on flat surface ($5\,\mathrm{km}/600\,\mathrm{m} \doteq 8$). Therefore, the length of the edge when its positive vertical ascend a is taken into account is $l((u,v)) + a_l a((u,v))$.

For the case of downhill rides, a positive vertical descend $d : E \to \mathbb{R}_0^+$ (cf. Figure 1) and a positive descend grade $d' : E \to \mathbb{R}_0^+$ are defined for the given edge $(u,v) \in E$ as following:

$$d((u,v)) := \begin{cases} h(u) - h(v) & \text{if } h(u) > h(v) \\ 0 & \text{otherwise} \end{cases}$$

$$d'((u,v)) := \frac{d((u,v))}{l((u,v))}$$

To model the speed acceleration caused by vertical descend for the given edge $(u,v) \in E$, a downhill speed multiplier $s_d : E \times \mathbb{R}^+ \to \mathbb{R}^+$ is defined as:

$$s_d((u,v), s_{\mathrm{dmax}}) :=$$

$$:= \begin{cases} s_{\mathrm{dmax}} & \text{if } d'((u,v)) > d'_c, \\ \frac{d'((u,v))}{d'_c}(s_{\mathrm{dmax}} - 1) + 1 & \text{otherwise} \end{cases}$$

where $s_{\mathrm{dmax}} \in \mathbb{R}^+$ is the maximum downhill speed multiplier, and $d'_c \in \mathbb{R}^+$ is the critical downhill grade d' value over which a downhill ride would take a multiplier of s_{dmax}. This is consistent with the reality that the acceleration is significant for the ride on a steep downslope (compared to a mild one) and is limited due to safety concerns, the physical limits of bicycles and the air drag. In this article, we limit the downhill speed by $s_{\mathrm{dmax}} = 2.5$ maximum downhill speed multiplier for the critical downhill grade $d'_c = 0.1$. This means that for an average speed of $s = 14$ km/h, the maximum downhill speed is 35 km/h when the downhill grade is 0.1 or greater.

3.2.1 Travel Time

We introduce the travel time criterion to provide a route with a shortest duration from an origin to a destination. Travel time plays an important role for cyclists especially when commuting. To model the slowdown caused by obstacle-category features such as stairs or crossings, a slowdown function $q : E \times \wp(F) \to \mathbb{N}_0^+$ is defined here which returns the slowdown in seconds on the given edge $(u,v) \in E$ with a set of features $f((u,v))$ (e.g., an additional constant time of 10 seconds is needed before each crossing of a road). Taking into account the integrated effect of the edge length, the change in elevation and its associated features, the travel time cost function is defined as:

$$c_{\mathrm{tt}}((u,v)) = \frac{l((u,v)) + a_l a((u,v))}{s \cdot s_d((u,v), s_{\mathrm{dmax}}) \cdot r_{\mathrm{tt}}(f((u,v)))} + q(f((u,v)))$$

where s is the average cruising speed of a cyclist. The criterion base value $r_{\mathrm{tt}}(f((u,v)))$ expresses how many times slower a cyclist can travel on a given edge $(u,v) \in E$ with a certain set of features $f((u,v))$ (e.g., on a road with bad surface). Intuitively, $c_{\mathrm{tt}}((u,v))$ models the travel time of flat rides, uphill rides, and downhill rides.

[6] The list of considered criteria is not exhaustive. In the future, we plan to take additional criteria into account, e.g., turn-frequency.

3.2.2 Comfort

The comfort criterion aims to provide a comfortable route from an origin to a destination. This criterion penalises bad road surface, obstacles such as steps, and places where the cyclist needs to dismount his or her bicycle. The comfort criterion base value r_{co} is weighted by the travel time c_{tt} spent on traversing the edge. The unit of the comfort criterion is seconds, so the criterion can be easily combined with the other criteria. It is based on the recognition that cyclists feel their travel time is shortened as they relish travel on comfortable cycleways (r_{co} is lower than 1). Thus the comfort cost function is defined as:

$$c_{\mathrm{co}}((u,v)) = c_{\mathrm{tt}}((u,v)) \cdot r_{\mathrm{co}}(f((u,v)))$$

The criterion base value $r_{\mathrm{co}}(f((u,v)))$ here express the comfort base value of the given edge $(u,v) \in E$ based on its properties $f((u,v))$, with small values indicating great comfort for riding.

3.2.3 Quietness

The goal of the quietness criterion is to find a quiet route with low or an absence of traffic. This criterion takes into account infrastructure for cyclists (e.g., dedicated cycleways), type of motor roads, and crossings. The quietness base value r_{qu} is also weighted by the travel time c_{tt} spent on traversing the edge; quiet cycleway segments $(u,v) \in E$ are assigned small values of $r_{\mathrm{qu}}(f((u,v)))$. Such function for quietness is defined as:

$$c_{\mathrm{qu}}((u,v)) = c_{\mathrm{tt}}((u,v)) \cdot r_{\mathrm{qu}}(f((u,v)))$$

3.2.4 Flatness

The goal of the flatness criterion is to find a route that minimises uphill rides. The cost function for the edge $(u,v) \in E$ for flatness takes into account positive vertical ascend a. We use a modification of Naismith's rule as in the travel time cost function. Instead of $a_l = 8$ that is used for the travel time, we use $a_p = 13$ that reflects how the uphill is percepted by the users. The value of a_p is set according to route choice model developed in the user study [2]. The cost function is then defined as:

$$c_{\mathrm{fl}}((u,v)) = \frac{a_p a((u,v))}{s} \cdot r_{\mathrm{fl}}(f((u,v)))$$

where $r_{\mathrm{fl}}(f((u,v))) = 1$ for all edges. In case of flat surface $c_{\mathrm{fl}}((u,v)) = 0$.

3.3 Cycle Planning Problem

In this section, we define the multicriteria cycle planning problem based on the cycleway graph G and a journey request r.

The *journey request* is a quadruple $r = (o, d, s, \overrightarrow{w})$ where $o \in V$ is an origin, $d \in V$ a destination, $s \in \mathbb{R}^+$ an average cycling speed, and $\overrightarrow{w} = (w_1, \ldots, w_k)$ a vector of criteria weights $w_i \in \mathbb{R}_0^+$ (i.e., a *profile*) that determine the importance of individual cost functions $c_i \in \overrightarrow{c}$. The *journey plan* $\pi = ((u_1,v_1), \ldots, (u_n,v_n))$ is defined as a sequence of $|\pi| = n$ edges $(u_j,v_j) \in E$. Edges represent the lowest-level, atomic parts of a journey plan.

To summarise, we define the *cycle planning problem* as a triple $C = (G, \overrightarrow{c}, r)$, where:

- $G = (V, E, g, h, l, f, F, \overrightarrow{r})$ is a *cycleway graph*
- $\overrightarrow{c} = (c_1, \ldots, c_k)$ is a *vector of cost functions*
- $r = (o, d, s, \overrightarrow{w})$ is a *journey request*

A *journey plan* π is then a solution of the cycle planning problem $C = (G, \overrightarrow{c}, r)$ if and only if the plan π forms a finite path from an origin o to a destination d in the cycleway graph G.

A journey plan π is an optimal solution of the cycle planning problem $C = (G, \overrightarrow{c}, r)$ if and only if the plan π minimises the total cost $c(\pi) = \sum_{j=1}^{|\pi|} \overrightarrow{w} \cdot \overrightarrow{c}(u_j,v_j)$ where $\pi = ((u_1,v_1), \ldots, (u_n,v_n))$, $\overrightarrow{c}(u,v)$ is a vector of cost functions for an edge $(u,v) \in E$, and $\overrightarrow{w}$ the vector of criteria weights (a profile).

4 Solution Method

In this section, we detail how the multicriteria cycle planning problem C is solved using an informed A* search [6]. In the next section, we describe how the real-world features represented in map data are reflected in the cost functions. In particular, we solve the cycle planning problem $C = (G, \overrightarrow{c}, r)$ by single-criteria A* search. We scalarise multiple criteria into one cost function $c : E \times \wp(F) \to \mathbb{R}_0^+$ using a vector $\overrightarrow{w} = (w_1, \ldots, w_k)$ of criteria weights called a profile:

$$c((u,v)) = \overrightarrow{c}((u,v)) \cdot \overrightarrow{w}$$

A* search needs a vector of heuristic functions $\overrightarrow{h} = (h_1, \ldots, h_k)$ with the same dimension k as the cost vector $\overrightarrow{c} = (c_1, \ldots, c_k)$. For the cost vector $\overrightarrow{c} = (c_{\mathrm{tt}}, c_{\mathrm{co}}, c_{\mathrm{qu}}, c_{\mathrm{fl}})$, we define the following vector of heuristic functions $\overrightarrow{h} = (h_{\mathrm{tt}}, h_{\mathrm{co}}, h_{\mathrm{qu}}, h_{\mathrm{fl}})$.

We define all heuristic functions as admissible, so that A* algorithm will find an optimal solution. We start with a heuristic function h_{tt} for travel time. Let $|(u,v)|$ be a direct distance between a node u and a node v. Then, the heuristic function h_{tt} from the current node u to a destination node d is defined as:

$$h_{\mathrm{tt}}((u,d)) = \frac{|(u,d)|}{s \cdot s_{\mathrm{dmax}} \cdot \max r_{\mathrm{tt}}}$$

Travel time heuristic function h_{tt} is admissible because the distance from a node u to a destination d is estimated using direct distance (always shorter or equal to a real distance) and in the denominator, maximal speed multiplier s_{dmax} and maximal value of the travel time base value r_{tt} is used.

The other heuristic functions h_{co} for comfort and h_{qu} for quietness are based on travel time heuristic function h_{tt}:

$$h_{\mathrm{co}}((u,d)) = h_{\mathrm{tt}}((u,d)) \cdot \min r_{\mathrm{co}}$$

$$h_{\mathrm{qu}}((u,d)) = h_{\mathrm{tt}}((u,d)) \cdot \min r_{\mathrm{qu}}$$

They are also admissible since the admissible travel time heuristic function h_{tt} is multiplied by a minimal value of the corresponding criterion base value.

Finally, we define the heuristic function h_{fl} for the flatness criterion. The heuristic function is based on the positive vertical ascend $a((u,d))$ between the current node u and the destination node d:

$$h_{\mathrm{fl}}((u,d)) = \frac{a_p a((u,d))}{s}$$

The flatness criteria heuristic function h_{fl} is admissible because the positive vertical ascend $a((u,d))$ between the current node u and the destination node d is the minimal positive vertical ascend that can be experienced in the route from the node u to node d (there are no downhills in the route).

Once we have defined the vector of heuristics functions $\overrightarrow{h}$, we can solve the cycle planning problem C by searching for a plan in the cycleway graph G using the A* algorithm which is using the defined heuristic functions.

5 Implementation

In this section, we describe how the map data are related with the criteria cost functions and profiles. At the beginning, map data are imported in the form of a graph structure annotated with map features, cf. Section 5.1. Based on the map features assigned to each node and edge, we define the criteria cost functions, cf. Section 5.2. Finally, we combine criteria cost functions using the profiles, cf. Section 5.3.

5.1 Data

OpenStreetMap (OSM) data is used to create the cycleway graph for the cycle planner. OSM is a project that creates and distributes free geographic data of Earth. The data are gathered by volunteers from the OSM mapping community. OSM data is distributed as an XML file through Planet OSM. OSM data is organised into three entities: nodes (which define points in space), ways (which define linear features and areas), and relations. The relations are used to define logical or geographic relations between the members of the relation. Ways, nodes, and relations can be members of relations. Each member has a role in a relation. For example, relations group motorways, bus routes or cycleways together. Relations, ways and nodes have various tags associated with them. Each tag is denoted by a key and a value. We denote the tags using `entity::key::value`, e.g., `way::highway::primary`. Latitude and longitude of each node is mapped to function g, altitude of each node is mapped to h. The following map elements relevant for cyclists are loaded according to the information from OSM tags associated with OSM nodes, ways, and relations. We divide the features into six categories:

- *Surface:* Surface quality in terms of smoothness of the surface and surface material, e.g., asphalt, gravel, or cobblestone.
- *Obstacles:* Steps and elevators.
- *Dismount:* Places where it is needed to dismount a bike, e.g., pavement, footway crossing.
- *For bicycles:* Description of the infrastructure for cyclists, e.g., dedicated cycleway, cycle lane, shared busway.
- *Motor roads:* Category of a road that is also used by cars, e.g., primary, secondary, residential, living street.
- *Crossings:* Crossings, crossroads, and traffic lights on the road.

Geographical locations of all nodes in the OSM data are represented as their latitude and longitude values using the World Geodetic System (version WGS 84), a *geographic* coordinate system type. In order to simplify the complex calculation of the Euclidean distance between two nodes expressed in the WGS 84 coordinates (the calculation is very frequently used in the A* Euclidean distance heuristic), we use a *projected* coordinate system. For locations in Prague, the spatial reference system "S-JTSK (Ferro) / Krovak" is used. The horizontal length l of each edge is calculated based on the projected coordinates. Elevation h for all nodes in the OSM data is acquired using the Shuttle Radar Topography Mission (SRTM) project.

When a filtered network of cycleways is created, it is not a strongly connected component. This means that based on the data, it is not possible to travel between the disconnected parts. We solve this issue by using only the largest strongly connected component.

5.2 OSM Tags Mapping

In this section, we map the categories of map features to the four criteria cost functions. The mapping is given in Table 1.

Table 1. Categories of map features to criteria cost functions mapping

Criteria cost function	Categories of map features
Travel time c_{tt}	Surface, Obstacles, Dismount
Comfort c_{co}	Surface, Obstacles, Dismount
Quietness c_{qu}	For bicycles, Motor roads, Crossings
Flattness c_{fl}	$\emptyset$

Table 2. Travel time and comfort criteria base values for features from the surface category

Entity	Key	Value	r'_{tt}	r'_{co}
way	smoothness	bad	0.7	3
way	smoothness	excellent	1	0.5
way	smoothness	horrible	0.5	2
way	smoothness	intermediate	0.8	1
way	smoothness	very_bad	0.6	4
way	surface	cobblestone	0.7	5
way	surface	compacted	0.9	1.5
way	surface	dirt	0.7	3
way	surface	grass	0.65	5
way	surface	gravel	0.5	5
way	surface	ground	0.6	4
way	surface	mud	0.4	5
way	surface	paving_stones	0.75	1.5
way	surface	sand	0.6	4
way	surface	setts	0.8	2
way	surface	unpaved	0.75	4
way	surface	wood	0.65	4

Then, we provide the criteria base values for each feature in the *surface* category. Due to article space restrictions, the definition of criteria base values for all categories is available in the git repository together with the cycle planner code, cf. Section 5.4. Effects of the OSM tags from the surface category on the travel time and comfort criteria are shown in Table 2. The effects are defined using the criteria base values for each feature: $r'_{\mathrm{tt}} : F \rightarrow \mathbb{R}^+$ for travel time and $r'_{\mathrm{co}} : F \rightarrow \mathbb{R}^+$ for comfort. Given that the function $f((u,v))$ returns features assigned to an edge $(u,v) \in E$, criteria base values r_{tt} and r_{co} are then computed as follows:

$$r_{\mathrm{tt}}(f((u,v))) = \min\{r'_{\mathrm{tt}}(p) | p \in f((u,v))\}$$

$$r_{\mathrm{co}}(f((u,v))) = \max\{r'_{\mathrm{co}}(p) | p \in f((u,v))\}$$

In case of the travel time base value r_{tt}, minimum value of r'_{tt} is used since we are interested in a feature that reduces the cyclist's speed s the most. In case of the comfort base value r_{co}, maximum value of r'_{co} is used since we take into account a feature that negatively affects the cyclist's comfort c_{co} the most.

5.3 Profiles

When searching for a cycle route, users have various preferences as it is summarised in Section 1. A *profile*, i.e., a vector $\overrightarrow{w} = (w_1, \ldots, w_k)$ of criteria weights $w_i \in \mathbb{R}_0^+$ determines the importance of individual cost functions. Weights w_i reflect the fact that for various users, certain factors of the path have different importance. The advantage of profiles is that they allow users to give a certain

Table 3. Evaluation results

Profile name	c_{tt} [s]	c_{co}*	c_{qu}*	a [m]	l [m]	Runtime [ms]	SD	# expanded nodes	SD
Commuting	3,271	1.12	1.21	150	9,001	214	157	51,748	36,265
Bike friendly	3,507	1.09	1.04	154	9,237	231	165	55,880	38,128
Flat	3,364	1.10	1.16	140	9,015	221	161	53,212	37,230
Fast	2,959	1.25	2.63	138	8,351	117	87	44,483	31,473

vector of weights a human understandable name that can be used for example in cycle planning application. In this article, we use four different profiles.

The *Commuting* profile $\overrightarrow{w}_{\mathrm{cm}} = (2, 1, 1, 1)$ is designed for people who use a bicycle for daily travelling to work or school. This profile attempts to find a quick but also comfortable, quiet, and reasonably flat route from an origin to a destination. This results in a profile that finds a quick route while prioritising cycleways, avoiding bad surface and steep ascends where possible.

The *Bike friendly* profile $\overrightarrow{w}_{\mathrm{bf}} = (1, 3, 5, 2)$ is designed to provide a path that is primarily quiet and then comfortable and avoiding steep segments. In contrast with the commuting profile, this profile is designed for non-commuting people who usually do not tolerate sharing a road with motor vehicles.

The *Flat* profile $\overrightarrow{w}_{\mathrm{fl}} = (1, 1, 1, 5)$ is designed for cyclists that want to avoid going uphill as much as possible. The other criteria (travel time, comfort, and quietness) are also considered to provide a route suitable for cyclists.

The *Fast* profile $\overrightarrow{w}_{\mathrm{fa}} = (1, 0, 0, 0)$ uses only the travel time criterion to provide a route with the shortest possible duration. This results in routes that might have more obstacles such as bad road surface or steeper cycleway segments. The target group for this profile are users with more experience and with a bicycle that can handle worse conditions.

5.4 Backend and Frontend

The algorithm backend of the cycle planner is implemented in JAVA 7. The code is available in a public git repository[7]. The results obtained in the evaluation are based on running the algorithm on one core of a 3.2 GHz Intel Core i7 processor of a Linux desktop computer with OpenJDK IcedTea7 2.4.4. The Osmosis 0.41 tool has been used to cut the Prague area from the OSM data dump. A* implementation from the AIMA 0.10.5 library has been used. To create the largest strongly connected component, the JGraphT 0.8.3 library has been used.

The cycle planner frontend is implemented using HTML and JavaScript. It uses the backend via a RESTful API that based on the journey request r returns a journey plan π formatted in the GeoJSON 1.0 data format. The cycle planner frontend allows users to select an origin and a destination by clicking in the map. They can enter their average cruising speed and select a profile. After the route is calculated, and journey plan is obtained, the interface displays the route and the elevation profile. A screenshot showing the web frontend with a found journey plan and elevation profile is depicted in Figure 2.

6 Evaluation

In this section, we evaluate our proposed approach on real-world cycleway network data for Prague. The cycleway graph G for Prague has 162,137 nodes and 358,468 edges.

[7] https://github.com/agents4its/cycleplanner/

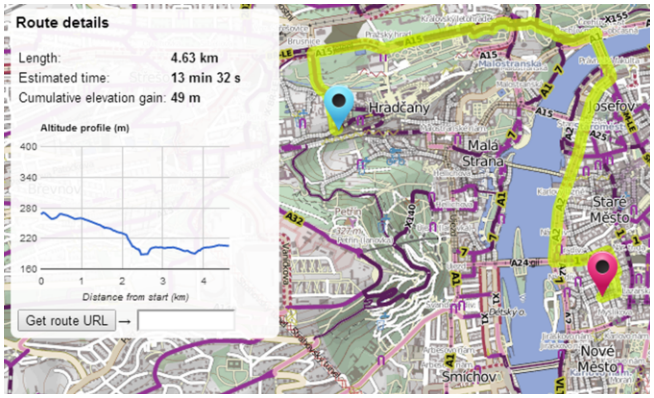

Figure 2. Cycle planner web frontend

We use four defined profiles for the evaluation of the algorithm (commuting $\overrightarrow{w}_{\mathrm{cm}}$, bike friendly $\overrightarrow{w}_{\mathrm{bf}}$, flat $\overrightarrow{w}_{\mathrm{fl}}$, and fast $\overrightarrow{w}_{\mathrm{fa}}$). The set of instances of the cycle planning problem Q for the experiment is created in the following way. First, n = 10,000 origin-destination tuples $Q_t = ((o_1, d_1), \ldots, (o_n, d_n))$ are sampled using the uniform distribution over the coordinates of Prague area. The origin-destination direct distance is limited to 10 km to prevent evaluating uncommonly long trips. Average bicycling velocity is set to $s = 14$ km/h.

Then the origin and destination coordinates are converted to origin and destination nodes from the cycleway graph G. Let $\delta(c)$ be a function that returns the nearest node in the cycleway graph G given a coordinate c. Then the set of $|Q|$ = 40,000 instances of the cycle planning problem is constructed. Each of the origin-destination tuples Q_t is combined with all profiles as follows:

$$Q = \{(G, \overrightarrow{c}, (\delta(o), \delta(d), s, \overrightarrow{w}))| \\ (o, d) \in Q_t \wedge \overrightarrow{w} \in \{\overrightarrow{w}_{\mathrm{cm}}, \overrightarrow{w}_{\mathrm{bf}}, \overrightarrow{w}_{\mathrm{fl}}, \overrightarrow{w}_{\mathrm{fa}}\}\}$$

A solution for each problem instance $C \in Q$ is computed. The overall results are shown in Table 3 where for all values it holds that lower values are better. The table shows averaged values of travel time criterion c_{tt}, comfort criterion c_{co}, and quietness criterion c_{qu}. Note that comfort and quietness criteria (marked with * in the table) are normalised by travel time. Then the table shows average positive vertical ascend a and average length of a journey plan l.

From the qualitative perspective, the Bike friendly profile is the best in comfort c_{co} and quietness c_{qu} criteria and the Fast profile is the best in travel time c_{tt} and has minimal positive vertical ascend a and also journey plan length l. The Commuting and the Flat profiles are good compromises between the four criteria, they provide a route with reasonably good comfort and quietness while keeping either travel time criterion or positive vertical ascend very low.

From the performance perspective, we measure average runtime in milliseconds per one journey request and average number of expanded nodes by the A* algorithm. The runtime of the A* search ranges from 117 ms for the Fast profile up to 231 ms for the Bike

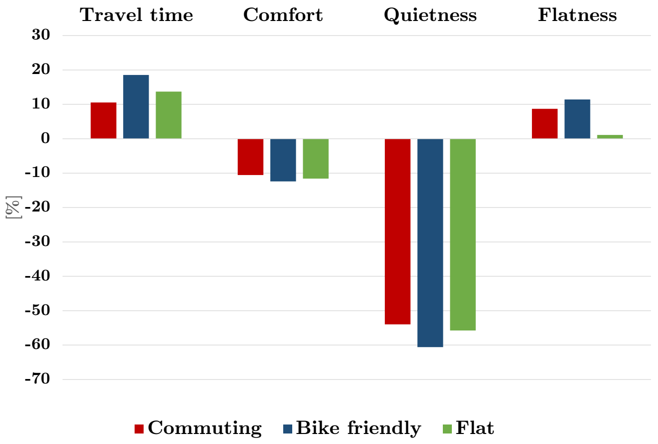

Figure 3. Relative comparison of average criteria values for the profiles. The baseline is the Fast profile. Lower values are better.

friendly profile. Given profile definitions in Section 5.3, the runtime is significantly affected by the number of criteria, that are taken into account. This is explained by the fact that Fast profile takes only travel time into account whereas the other profiles take into account all four criteria. Number of expanded nodes ranges from 44 to 55 thousands, i.e., from 27% to 34% of all nodes in the cycleway graph G.

In addition to absolute values given in Table 3, Figure 3 shows a relative comparison of the profiles. We use the Fast profile as a baseline. On the one hand, in the travel time criterion, Commuting profile is better than Bike friendly profile by 8%. On the other hand, Bike friendly profile is better by 7% in the quietness criterion. From the comfort criterion perspective, the profiles are very balanced (the differences are around 1%). In Figure 4, it can be observed that different profiles produce different journey plans.

7 Conclusion

We have formalised and solved a multicriteria cycle route planning problem and showed how the solution can be implemented and practically deployed. Based on recent studies on cyclists' route choice, our planner considers a broad range of transport network features, including the length of each cycleway segment, elevation, surface of the road, obstacles, dismount sections, infrastructure for cyclists, categories of motor roads, and crossings. Route optimisation is performed with regards to four criteria (travel time, comfort, quietness, and flatness) whose relative weights are tailored to the needs of specific cyclist groups by the concept of profiles (Commuting, Bike friendly, Flat, and Fast). Experiments based on Prague OpenStreetMaps data have confirmed that our solution can return high-quality journey plans in less than 250 milliseconds per one query.

As future research, we would like to investigate a fully multicriteria solution of the cycle planning problem to receive a full Pareto optimal set of solutions, e.g., by using NAMOA* algorithm [10]. In addition, the criteria base values could be fine-tuned using the feedback from the cycling community. Finally, the cycle planning problem might take into account additional parameters such as departure time, turns penalisation, real-time traffic information, or real-time weather information.

Demonstration version of the cycle planner can be accessed through http://agents4its.net.

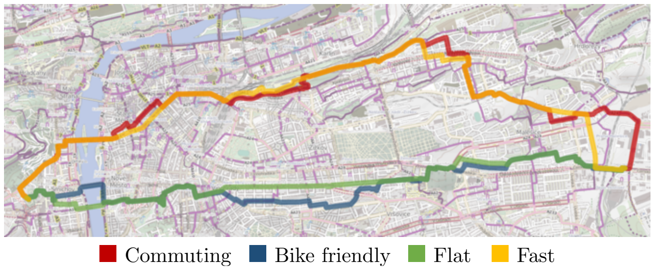

Figure 4. Different journey plans for different profiles

ACKNOWLEDGEMENTS

Supported by the European Union Seventh Framework Programme FP7/2007-2013 (grant agreement no. 289067), by the Ministry of Education, Youth and Sports of Czech Republic (grant no. 7E12065), by the Czech Technical University (grant no. SGS13/210/OHK3/3T/13), and by the European social fund within the framework of realising the project "Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague", CZ.1.07/2.3.00/30.0034.

REFERENCES

[1] H. Bast, D. Delling, A. Goldberg, M. Muller-Hannemann, T. Pajor, P. Sanders, D. Wagner, and R. Werneck, 'Route Planning in Transportation Networks', Technical report, Microsoft Research, (2014).

[2] J. Broach, J. Dill, and J. Gliebe, 'Where do cyclists ride? A route choice model developed with revealed preference GPS data', *Transportation Research Part A: Policy and Practice*, **46**(10), 1730 – 1740, (2012).

[3] C. Dora and M. Phillips, *Transport, environment and health*, WHO Regional Office for Europe, Copenhagen, 2000.

[4] Filler, V. (AUTO*MAT) Private communication, 2013-11-18. Why a cycle planner is important for cyclists.

[5] R. Geisberger, P. Sanders, D. Schultes, and D. Delling, 'Contraction Hierarchies: Faster and Simpler Hierarchical Routing in Road Networks', in *Proceedings of the 7th international conference on Experimental algorithms*, WEA'08, pp. 319–333. Springer-Verlag, (2008).

[6] P. Hart, N. Nilsson, and B. Raphael, 'A Formal Basis for the Heuristic Determination of Minimum Cost Paths', *IEEE Transactions on Systems Science and Cybernetics*, **4**(2), 100–107, (February 1968).

[7] David Herlihy, *Bicycle: the history*, Yale University Press, 2004.

[8] H. H. Hochmair, 'Towards a classification of route selection criteria for route planning tools', *Developments in Spatial Data Handling, Springer, Berlin*, 481–492, (2004).

[9] H. H. Hochmair and J. Fu, 'Web Based Bicycle Trip Planning for Broward County, Florida', in *ESRI User Conference*, (2009).

[10] L. Mandow and J. De La Cruz, 'Multiobjective A* search with consistent heuristics', *J. ACM*, **57**(5), (June 2008).

[11] Philip Scarf, 'Route choice in mountain navigation, Naismith's rule, and the equivalence of distance and climb', *JOURNAL OF SPORTS SCIENCES*, **25**(6), (April 2007).

[12] J. G. Su, M. Winters, M. Nunes, and M. Brauer, 'Designing a route planner to facilitate and promote cycling in Metro Vancouver, Canada', *Transportation Research Part A: Policy and Practice*, **44**(7), 495–505, (2010).

[13] I. Tal, A. Olaru, and G. Muntean, 'eWARPE - Energy-efficient Weather-aware Route Planner for Electric Bicycles', in *IEEE International Conference on Network Protocols (ICNP)*, Gottingen , Germany, (2013).

[14] R. J. Turverey, D. D. Cheng, O. N. Blair, J. T. Roth, G. M. Lamp, and R. Cogill, 'Charlottesville bike route planner', in *Systems and Information Engineering Design Symposium (SIEDS)*, (2010).

[15] M. Winters, G. Davidson, D. Kao, and K. Teschke, 'Motivators and deterrents of bicycling: comparing influences on decisions to ride', *Transportation*, **38**(1), 153–168, (2011).