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Pokročilé plánování multimodálních cest a tras

Advanced Multimodal Journey and Route Planning

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Abstract

The growing complexity of transport systems and the need to make their use as simple as possible drives the development of advanced software tools that would help people make right travel decisions. In this lecture, I present my contributions to solving several categories of the trip and routing planning problems from the modelling, algorithmic as well as software engineering perspective. First I will talk about *fully multimodal* trip planning, i.e., the trip planning capable of finding trip plans utilizing the whole range of transport means and their combinations. Here, my main contribution comprises a novel *metaplanning-based* approach to trip planner integration through which fully multimodal planning can be implemented on top of multiple existing planners that only have partial transport mode and/or geographical coverage. Second, I will talk about *urban bicycle route planning* with realistic route choice models. Here, my main contribution concerns the multicriteria formalization of bicycle routing problem and speed-up techniques for its efficient solution. Third, I will briefly talk about route planning in cooperative and non-cooperative multiagent settings. After describing my research contributions to the above three categories of trip planning problems, I will talk about real-world applications of my research results. Finally, I will conclude with a list of interesting open problems in trip planning and an outlook for my future research.

Summary

Zvětšující složitost dopravních systému a potřeba udělat jejich používání co nejsnadnější motivuje vývoj pokročilých softwarových nástrojů, které lidem pomůžou udělat správná rozhodnutí o jejich cestách. V této habilitační přednášce představím své výzkumné příspěvky k řešení několika kategorie problémů plánování cest a tras, a to je z perspektivy formální reprezentace, algoritmů i softwarové implementace. Nejprve budu hovořit o plně multimodálním plánování, tj. plánování, které je schopno nalézt cesty využívající všechny typy dopravních prostředků a jejich kombinací. Zde můj hlavní příspěvek zahrnuje nový tzv. metaplánovací přístup k integraci plánovačů cest, který umožnuje implementovat plnou multimodalitu nad existujícími plánovači, které podporují jen některé dopravní prostředky nebo vybrané oblasti. Za druhé budu hovořit o plánování tras pro městkou cyklistiku s realistickými modely výběru tras. Zde je mým hlavním příspěvkem multikriteriální formalizace problému hledání cyklistických tras a urychlovací techniky pro jeho efektivní řešení. Za třetí krátce pohovořím o mých výzkumných příspěvcích do problematiky plánování tras v kooperativních a nekooperativních multiagentních scénářích. Po představení mých výzkumných příspěvků k výše uvedených oblastech pohovořím o aplikací mých výsledků v praxi. Na závěr představím seznam zajímavých otevřených problému a nastíním svého budoucí výzkumné plány.

Klíčová slova

multimodální plánování cest, plánování cyklistických tras, grafové algoritmy, optimalizace, inteligentní dopravní systémy.

Keywords

multimodal trip planning, bicycle routing, graph algorithms, optimization, intelligent transport systems.

Contents

1 Introduction

The growing complexity of transport systems and the need to make their use as simple as possible drives the development of advanced software tools that would help people make right travel decisions. Although numerous variants of trip and route planning problems have been studied for several decades (see e.g. [1] for a recent comprehensive review), the problem is far from solved. On the contrary, the on-going technological and societal developments – related e.g. to sustainable multimodal urban mobility, on-demand transport systems or electric vehicles – keep bringing new travel planning challenges that need to be addressed.

In this lecture, I will describe several of such challenges and will discuss my research and engineering contributions to their solution.

2 Fully Multimodal Journey Planning

My first contribution concerns fully multimodal journey planning in the urban context. The advent of new types of mobility services, such as bike, electric scooter or car sharing, real-time carpooling or next-generation taxi, has further expanded the already rich portfolio of means of travel available in modern cities. Providing intelligent tools that would help citizens make the best use of the mobility services on offer is thus needed more than ever. Existing journey planners address this need only partially – in particular, they only consider a limited subset of transport modes and their combinations and do not have full support for working with real-time information.

2.1 Generalized Time-Dependent Graphs

This is why, together with my students, I have conducted research on *fully* multimodal journey planning that supports the full spectrum of available mobility services and their combinations. In our approach, a journey can consist of any combination of scheduled public transport modes (e.g., bus, tram and underground), individual modes (e.g., walk, bike, shared bike and car), and on-demand (e.g., taxi) modes.

We have adopted a representation-centric approach to solving the fully multimodal journey planning problem. Instead of providing purpose-specific journey planning algorithms, we have introduced *generalised time-dependent (GTD) graphs* that allow representing the fully multimodal journey planning problem as a standard graph search problem and consequently allow using general shortest path algorithms to solve

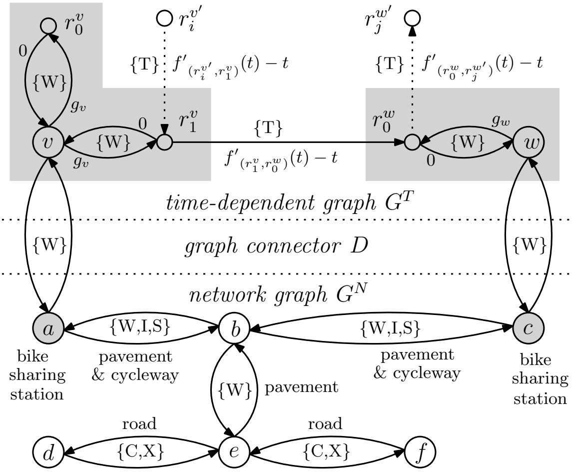

Figure 1: An example of the GTD graph. Edges are annotated with the permitted modes of transport. Stop nodes $v, w \in S$ represent two tram stops that are connected by one tram route connecting four route nodes $(r_i^{v'}, r_1^v, r_0^w, r_j^{w'})$. Route nodes $R_v = \{r_0^v, r_1^v\}$ and $R_w = \{r_0^w\}$ associated with the respective stop nodes v and w are highlighted with grey background. Edges from the time-dependent graph G^T are also annotated with their weight (edge traversal time).

it. Importantly, this approach allowed us to reuse the GTD representation and associated tools for a wide range of additional applications. The GTD graph is a generalisation of the time-dependent graph with constant transfer times defined by Pyrga et al. [13] (the time needed to make a transfer between two lines at a stop is defined as a constant for each stop). The generalised time-dependent graph G is constructed from the following three structures: (1) *time-dependent graph* G^T for the PT network; (2) *network graph* G^N for the network of pavements, cycleways, and roads; (3) *graph connector* D of the time-dependent graph G^T and the =network graph G^N. Figure 1 shows and describes a fragment of the GTD graph; Figure 2 then visualizes a GTD graph for the Milan metropolitan area.

In a subsequent development, we have further extended our GTD representation to support time-varying historic and real-time information about conditions in the transport system (i.e., actual traffic flow speeds, delays and disruptions in the public transport network, or the availability of bicycles in bike-sharing stations).

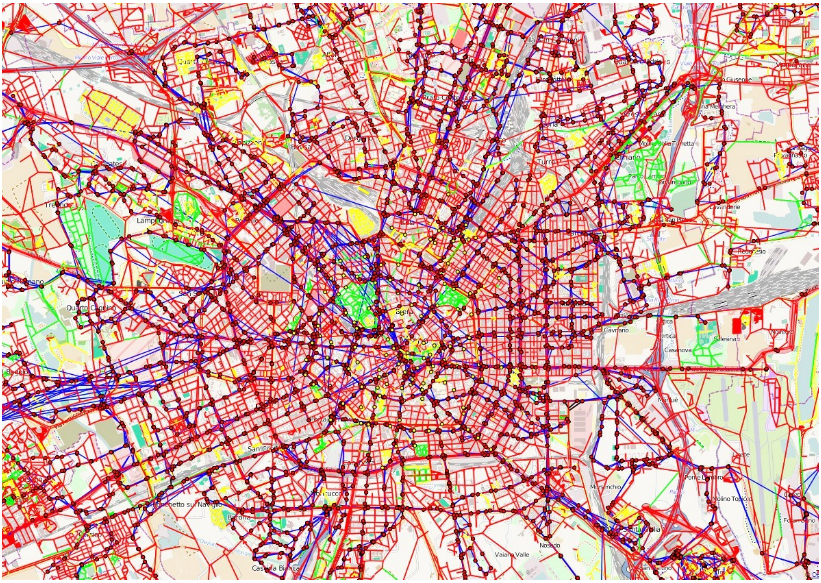

Figure 2: A visualization of the generalised time-dependent graph representing the multimodal transport network of Milan, Italy.

2.2 Metaplanning-based Approach To Trip Planner Integration

Although in principle, providing a *fully* multimodal journey planner supporting the planning with all types of transport services and their combinations is now algorithmically possible, providing such fully multimodal journey planning in practice remains elusive. This situation is largely caused by the fact a fully multimodal journey planner requires a wealth of detailed data about all transport services and these are often difficult and/or costly to obtain.

This why in my more recent work, I, together with my students, have developed a novel, elegant approach to overcome the problem. The approach is based on *trip planner integration* – it obtains a fully multimodal journey planning capability by interconnecting, in a smart way, multiple incomplete journey planners (termed *subplanners*), each with only limited modal and/or geographical coverage. The integration relies on a planning metagraph, a simplified representation of the underlying transport system which can be build with only a minimum amount of data.

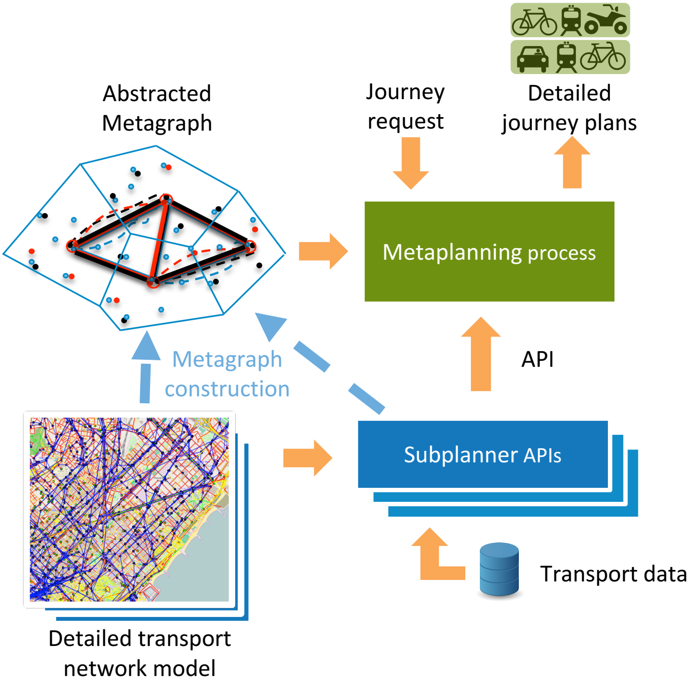

Figure 3: An overview of the metaplanning approach.

We solve the problem in two phases. In the *metasearch phase*, we use standard single-criterion or multicriteria shortest path algorithms to search the metagraph. We find a set of *metaplans* that consist of a sequence of *metalegs*, i.e., sequences of metaedges with the same mode of transport. In the *plan refinement phase*, each metaplan is refined using provided subplanners. The output of the plan refinement phase is a set of *detailed journey plans* which is the solution of the fully multimodal journey planning problem. A scheme outlining the metaplanning approach is given in Figure 3.

We have recently tested the metaplanning approach in real-world conditions of the greater metropolitan area of Barcelona. The results have confirmed the feasibility of the approach to achieve good-quality fully multimodal plans with the metaplanner response time in the range of seconds. A more thorough evaluation of the results is currently underway.

3 Bicycle Routing with Realistic Route Choice Preferences

In contrast to car and public transport journey planning, for which advanced algorithms and mature software implementations exist [1], bicycle route planning is a surprisingly underexplored topic. Although numerous bicycle route planning applications have recently emerged (e.g., Cyclestreets[1] or BBBike[2]), these applications follow ad-hoc approaches and provide very little information about their internal models and search algorithms.

Interestingly and importantly, compared to car drivers, cyclists consider a significantly broader range of factors while deciding their routes. By employing questionnaires and GPS tracking, researchers have found that besides travel time and distance, cyclists are sensitive to slope, turn frequency, junction control, noise, pollution, scenery, and traffic volumes [3]. Moreover, the relative importance of these factors varies among cyclists and can also be affected by weather conditions and the purpose of the trip [3]. Such a user- and context-dependent multi-criteriality makes bicycle routing a particularly difficult category of routing problems.

This is why together with my students and postdocs, I have conducted research on bicycle routing that takes realistic route choice preferences into account.

3.1 Formalizing Bicycle Routing as a Shortest Path Problem

Our first contribution to bicycle routing has been a proper formalization of the multi-criteria bicycle routing problem. Although relatively straightforward, such a formalization had not been previously available. The flexible, hierarchical model we have developed relies on sets of features, criteria and costs to capture the rich semantic information contained in the underlying transport network map data in a form amenable to multi-criteria shortest path search.

On a formal level, we represent the cycleway network as a weighted directed connected *cycleway graph* $G = (V, E, \overrightarrow{c})$, where V is the set of nodes representing start and end points (i.e., cycleway junctions) of cycleway segments and $E \subseteq \{(u, v)|(u, v \in V) \wedge (u \neq v)\}$ is the set of edges representing cycleway segments. The cycleway graph is directed

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[1] `http://www.cyclestreets.net/`

[2] `http://www.bbbike.org/`

due to the fact that some cycleway segments in the map are one-way only. The cost of each edge is represented as a k-dimensional vector of criteria $\overrightarrow{c} = (c_1, c_2, \ldots, c_k)$. The non-negative cost value c_i of i-th criterion for the given edge $(u, v) \in E$ is computed by the cost function $c_i : E \to \mathbb{R}_0^+$. The *multi-criteria bicycle routing problem* is then defined as a triple $C = (G, o, d)$:

- $G = (V, E, \overrightarrow{c})$ is the *cycleway graph*
- $o \in V$ is the route origin
- $d \in V$ is the route destination

A route π, i.e., a finite path π with a length $|\pi| = n$ from the origin o to the destination d in the cycleway graph G has an additive cost value

$$\overrightarrow{c}(\pi) = \left(\sum_{j=1}^{|\pi|} c_1(u_j, v_j), \ldots, \sum_{j=1}^{|\pi|} c_k(u_j, v_j) \right)$$

The solution of the multi-criteria bicycle routing problem is a full Pareto set of routes $\Pi \subseteq \{\pi | \pi = ((u_1, v_1), \ldots, (u_n, v_n))\}$ non-dominated by any other solution (a solution π_p dominates another solution π_q iff $c_i(\pi_p) \leq c_i(\pi_q)$, for all $1 \leq i \leq k$, and $c_j(\pi_p) < c_j(\pi_q)$, for at least one j, $1 \leq j \leq k$).

Based on the studies of real-word cycle route choice behaviour [17, 3], we further consider a tri-criteria bicycle routing problem. The formulation of the problem is a compact version of the earlier formulation proposed in [15] and considers the following three route-choice criteria: *travel time*, *comfort* and elevation gain. Detailed description of the criteria is beyond the scope of this talk and can be found in [7].

3.2 Efficient Algorithms for Bicycle Routing

Our second contribution to bicycle routing focused more on the algorithmic part of the problem. We applied the *multiple label setting* (MLS) algorithm [10] for finding a full set of Pareto routes in a multi-criteria bicycle routing problem. To reduce the potentially very large number of Pareto solutions, we have introduced a route selection algorithm, based on hierarchical clustering, for extracting a small representative subset of Pareto routes [14].

The major issue with the standard multiple label setting algorithm is its very long running time – producing a full set of Pareto routes on a cycleway graph covering a larger city can easily take ten of minutes – which is far beyond the response time suitable for interactive applications. In order to speed up the multi-criteria search, we have therefore developed a *heuristic-enabled* multiple label setting algorithm which uses several heuristics to radically reduce route search times. More specifically, we have employed the following heuristics:

- **Ratio-Based Pruning:** The ratio-based pruning terminates the search (long) before the priority queue gets empty (which means that the whole search space has been explored). A pruning ratio $\alpha \in \mathbb{R}^+$ is defined and the search is terminated when one of the criteria cost values, e.g., $l_1(u)$, in the *current* label exceeds α times the best so far value of the same criterion for a route that has already reached the destination.

- **Cost-Based Pruning:** This heuristic does not expand the search to a label $L(v)$ which is very close in the cost space (criteria $c_1, \ldots, c_k$) to the existing non-dominated labels at the node v. The newly generated label $L(v)$ with a closer Euclidean distance than $\gamma \in \mathbb{R}^+$ is discarded. Therefore, the search process is accelerated since fewer labels are inserted into the queue and the bag.

- **Buckets:** This heuristic, originally defined in [5], discretizes the cost space using buckets for the criteria values. A function $bucketValue : \mathbb{R}_0^+ \to \mathbb{N}$ is used to assign a real cost value l_i an integer bucket value $bucketValue(l_i)$.

3.3 Evaluation and Results

To evaluate our approach, we consider the real cycleway network of Prague. Prague is a challenging experiment location due to its complex geography and fragmented cycling infrastructure, which raises the importance of proper multi-criteria routing. In order to evaluate the performance of proposed speed-up heuristics, we employ two categories of evaluation metrics: *speed* and *quality*. The primary heuristics to measure the algorithm speed is the average runtime in milliseconds for each origin-destination pair.

The choice of the quality metric is more complicated. This is because for a multi-criteria optimisation problem, solution quality cannot be simply defined in terms of closeness to an optimal solution – instead, we define solution quality in set terms as the closeness to the full Pareto set. To our best knowledge, there is not a universal way to evaluate the quality of multi-criteria solutions. As the primary quality metric, we have thus decided to use the average distance $d_c(\Pi^*, \Pi)$ of the heuristic Pareto set Π from the optimal Pareto set Π^* in the cost space. Distance $d_c(\pi^*, \pi)$ between two routes π^* and π is measured as the Euclidean distance in the unit three-dimensional space of criteria values normalised to the $[0, 1]$ range.

For each graph evaluation area, a set of 300 origin-destination pairs generated randomly with a uniform spatial distribution, was used in the evaluation. The minimum origin-destination distance is set to 500 m. The longest routes have approximately 4.5 km. We executed the standard MLS algorithm and all 15 heuristic combinations using the same generated 300 origin-destination pairs. Therefore, each heuristic combination is evaluated on 300 origin-destination pairs.

The results of the empirical evaluation are summarized in Figure 4. More details about the evaluation can be found in [7].

Finally, we have chosen a hilly area in Zizkov, Prague 3 to illustrate the Pareto set of routes in the physical space. In Figure 5, we illustrate the route distribution of the Pareto sets returned by the MLS algorithm and three different heuristic combinations. Each subfigure is provided with the name of the heuristic combination, the size of the Pareto set (ranges from 532 to 6 routes) and the algorithm runtime (ranges from 90 seconds to 378 ms). The more routes use a given cycleway network segment, the wider is the depicted line. It can be observed that the heuristics return a Pareto set of routes that very well corresponds to the optimal Pareto set.

To summarise, we have evaluated 15 different combinations of heuristics from which 9 combinations dominated the others in terms of quality and speed. The heuristics offer significant *one to four orders of magnitude speedup* over the MLS algorithm in terms of average runtime. The speedup is achieved by lowering the number of iterations and also the number of dominance checks in each iteration. *MLS+Ellipse* is the best heuristic in terms of quality of the produced Pareto set while *MLS+Ellipse+Ratio+Epsilon* is the best heuristic in terms of average runtime. Taking into the account the trade-off between the quality of a solution and the provided speedup, we consider *MLS+Ellipse+Epsilon* heuristic to have the best ratio between the quality and speed.

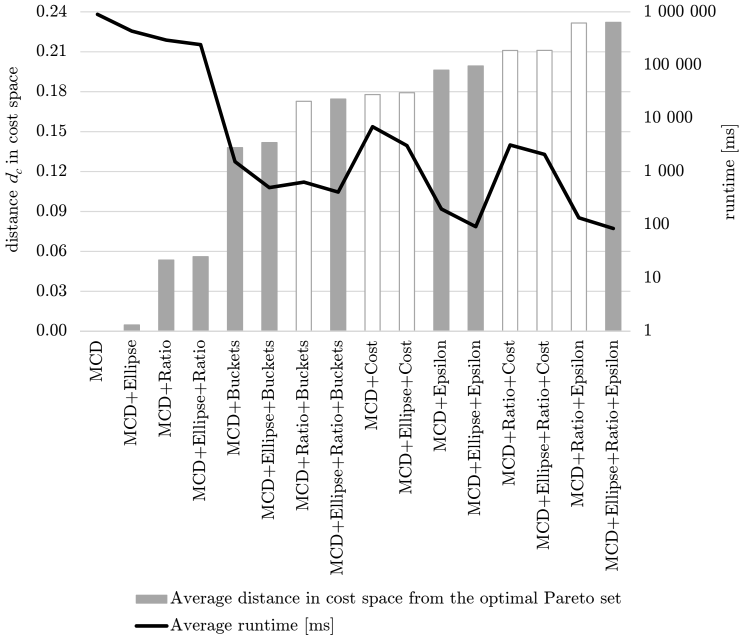
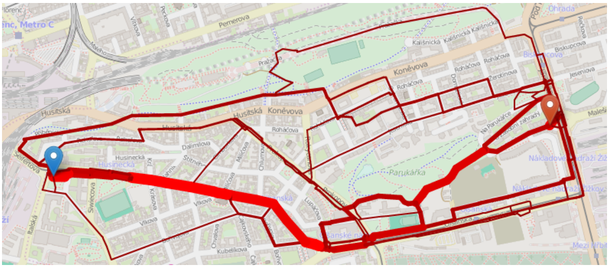


Figure 4: Speed and quality for the MLS algorithm and all heuristic combinations sorted by the quality from the best (MLS on the left hand side) to the worst. Non-dominated heuristic combinations have grey filled-in bars.

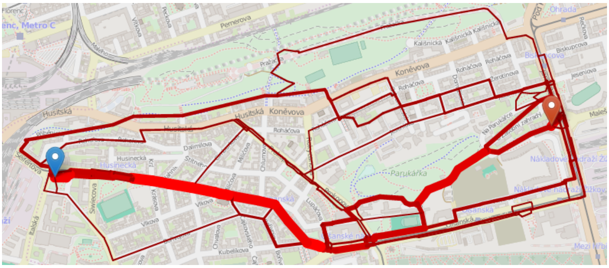
4 Multi-agent Problems in Trip and Route Planning

Apart from the fully multimodal trip planning and multi-criteria bicycle routing, I have also conducted research on two types of *multiagent* trip and routing planning problems:

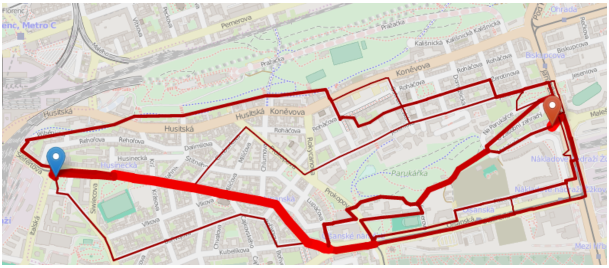
- *Planning Shared Journeys on Timetabled Transport Services* – I have contributed to the development of a novel agent-based approach for planning shared trips on public transport [6]. The approach employs the recently introduced domain-independent *best-response multiagent planning* [9] and specializes it for the specific purpose of planning shared journeys on timetabled transport services. The key benefit of the approach is its scalability to real-world public transport networks.



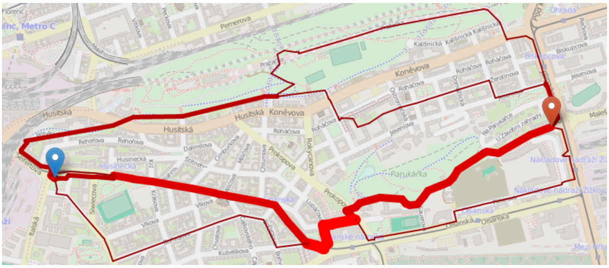
(a) MLS, optimal Pareto set with 532 routes, 90 s



(b) MLS+Ellipse+Ratio, 500 routes, 32 s



(c) MLS+Ellipse+Buckets, 26 routes, 623 ms



(d) MLS+Ellipse+Ratio+Epsilon, 6 routes, 378 ms

Figure 5: Pareto sets for the MLS algorithm and three heuristics.

- *Route Planning in Adversarial Scenarios* – Together with my students, I also worked on route planning in adversarial settings, which represents a very challenging variant of route planning problems. Assuming the ability of agents to reason about the actions and strategies of the opponent, such route planning problems are best studied within the context of non-cooperative game theory. I specifically worked on two variants of adversarial route planning problem. In the first variant, the agent needs to find a route crossing a controlled area such that the agent avoids (or maximizes the probability of avoiding) being detected and/or intercepted by the adversary. In the other variant of the problem, the agent needs to find a patrolling route around a sensitive asset such that the chance of an adversary successfully attacking the asset is eliminated or at least minimized. More details about the problems studied and the results achieved can be found in [2] and [16].

Overall, the work on route planning in adversarial domains has revealed the combinatorial challenges of route planning with strategic, game-theoretic models. While in the standard journey planning setting, transport networks comprising millions nodes and edges can be efficiently searched, even significantly smaller problems (thousands of nodes) can become hard to solve when considered in the adversarial, game-theoretic setting.

5 Real-World Applications

I consider my research incomplete until its results are validated on real-world problems. That's why I like to work in close collaboration with the intended users of my research and with those who understand how the new research findings can be turned into usable real-world applications. In the case of fully multimodal journey planning such collaborations has been primarily taking place as part of collaborative international research projects.

More specifically, the results of our research on real-time fully multimodal planning have been integrated in the core journey planning subsystem[8] of the SUPERHUB platform for sustainable multimodal urban travel, developed under the *SUstainable and PERsuasive Human Users moBility in future cities (SUPERHUB)* [3] project [4]. Through the SUPERHUB project field trials, our journey planning algorithms

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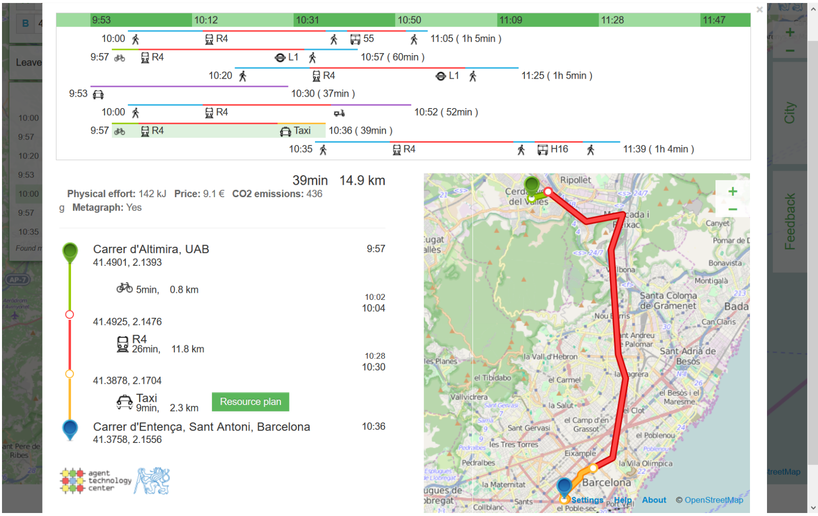
[3] `http://superhub-project.eu/`



9:53 10:12 10:31 10:50 11:09 11:28 11:47

10:00 R4 55 11:05 (1h 5min)
9:57 R4 L1 10:57 (60min)
10:20 R4 L1 11:25 (1h 5min)
9:53 10:30 (37min)
10:00 R4 10:52 (52min)
9:57 R4 Taxi 10:36 (39min)
10:35 R4 H16 11:39 (1h 4min)

39min 14.9 km
Physical effort: 142 kJ **Price:** 9.1 € **CO2 emissions:** 436 g **Metagraph:** Yes

Carrer d'Altimira, UAB 41.4901, 2.1393	9:57
5min, 0.8 km	10:02 10:04
41.4925, 2.1476	
R4 26min, 11.8 km	10:28 10:30
41.3878, 2.1704	
Taxi 9min, 2.3 km	
Carrer d'Entença, Sant Antoni, Barcelona 41.3758, 2.1556	10:36

Figure 6: Example fully multimodal trip plans produced by the meta-planner approach in the Barcelona metropolitan area.

were successfully tested by several thousand users in four big European cities (Barcelona, Milan, Helsinki and Brno).

The results of our research on metaplanning-based trip planner integration have been integrated into the trip planning core of the MyWay trip planning platform, developed under the *European Smart Mobility Resource Manager (MyWay)* project[4]. Examples of fully multimodal trips produced by the system are shown in Figure 6. In the coming months, the capabilities and performance of our metaplanning techniques are going to be tested with hundred users in Catalonia, Berlin and Trikala (Greece).

Futhremore, the generalized time-dependent representation and selected journey planning algorithms have also been leveraged in our research on analysing accessibility in multimodal transport systems [12, 11]. Importantly, our research on transport accessibility analysis has been integrated into a working prototype of an online transport network analyser, which is available, at the time of writing, at `http://transportanalyser.com`. Since its launch in September of 2013, the online transport analyser has been used by several thousand users.

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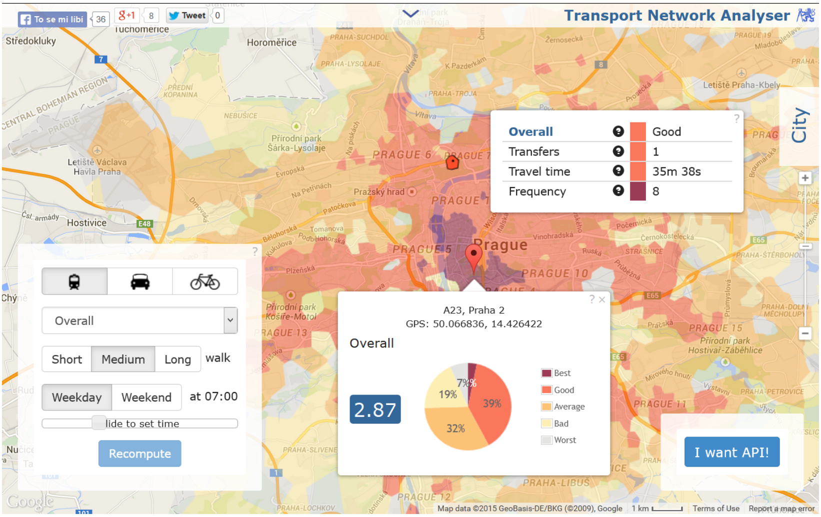
[4] `http://myway-project.eu/`



Overall: Good
Transfers: 1
Travel time: 35m 38s
Frequency: 8

A23, Praha 2
GPS: 50.066836, 14.426422
Overall
2.87

Figure 7: A prototype web application for the fine-grained analysis of multimodal transport accessibility.

My research on urban bicycle routing has also already found its way to practical applications. Based on our models and algorithms, we have developed both a smartphone- and web-based working prototypes of bicycle routing and navigation systems. Since its release in May 2015, the smartphone-based application (see Figure 8) has been used by more than 1000 thousand users. Both the web-based and mobile-version of our cycle routing applications are available, at the time of writing, to the public at `http://cykloplanovac.cz`.

6 Conclusions and Outlook

Over the past years, I and my collaborators have acquired a firm grounding in the problems and solution techniques at the cross-section of multiagent systems, artificial intelligence and transport research. We have acquired a solid understanding of relevant formal models and algorithms, developed a modular stack of reusable software components, assembled a broad range of crucial real-world transport data sets and built strong links with a number of key academic and industrial players in the field. In the future, we aim to capitalize on these achievements and continue contributing strongly to the theory and practise of intel-

Figure 8: A prototype cycling navigation application utilizing base multi-criteria cyclerouting models and algorithms.

ligent transport systems and computational transportation science.

In the context of trip and route planning, there are several topics I would like to address:

- *Automated building and maintenance of planning graphs* – The practical experience with building several full-stack trip and route planning systems made me acutely aware that a major barrier for the real-world deployment of advanced trip planning systems nowadays is generally *not* the lack of efficient algorithms but the insufficient availability and/or quality of data required to build accurate and up-to-date instances of respective trip planning problem. The richer and the more comprehensive the formulation of the trip planning problem is, the more extensive is the list data sources and data formats that need to be processed and integrated. Errors in input data are relatively common which, combined with multiple data formats used, makes the input data processing and integration a tedious and error-prone task. The development of (semi-)automated techniques that could detect defects in the input data and/or automatically fix certain types of frequent data issues could radically speed up the creation and maintenance of trip planning graphs and, consequently, the real-world deployment of advanced trip planning solutions.

- *Integration of trip planning and machine learning* – The fast increasing amount of transport data open new opportunities for using data analysis and machine learning for improving the quality of trip planning results. In this context, I aim to focus on the problem of exploiting real-world GPS tracks to improve urban bicycle routing algorithms. The effort, which I have already started with one of my Ph.D. students, will first look at learning cyclist's route choice models from the observation of routes cyclists choose to take. Whether a cyclist is going to choose a particular street to go through depends both on the local attributes of the street as well as on non-local attributes related the centrality of the respective edge in the cycleway graph. Decoupling these two factors and consequently being able to quantify their influence is a challenging task I would like to address utilizing the real-word tracks data we have collected using our cyclenavigation application.

- *Integrated multimodal trip planning and transport service reservation* – The ability to have tickets and reservations required for a trip automatically arranged is crucial for the concept of seamless door-to-door mobility. We have already made initial steps in this directions by introducing the concept of trip plan *resourcing*. A principled solution of the problem, however, will require an in-depth exploration of how planning and resource allocation should be mutually combined to provide reliable journey plans in capacity-limited environment.

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7 Ing. Michal Jakob, Ph.D.

Employment

- **Czech Technical University in Prague, Faculty of Electrical Engineering, Prague, CZ (2006-now)**
  Research scientist, lecturer and group leader.
- **BT Group, Pervasive ICT Research Centre, Ipswich, UK (2004-2006)**
  Research scientist.
- **Illusion Softworks, Praha (2003-2004)**
  Computer game artificial intelligence programmer.

Education

- **Ph.D. in Artificial Intelligence and Biocybernetics (2008)**
  Czech Technical University in Prague, Faculty of Electrical Engineering, Prague, CZ.
- **M.Sc.-equivalent in Computer Science (2001)**
  Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Prague, CZ.

Selected Research Grants

- **MyWay: European Smart Mobility Manager (2013-[2016])**
  Principal co-investigator. Funded by EC under FP7 - grant agreement 289067.
- **RODOS: ROzvoj Dopravních Systêmů (2012-[2018])**
  Principal co-investigator. Funded by TAČR - grant agreement TE01020155.
- **SUPERHUB: SUstainable and PERsuasive Human Users moBility in future cities (2011-2014)**
  Principal co-investigator. Funded by EC under FP7 - grant agreement 609023.

Teaching

- **Multiagent Systems – lecturer (2010-now)**
  (Open Informatics study programme)
- **Artificial Intelligence for Robotics – lecturer (2010)**
  (Cybernetics and Robotics study programme)
- **Bachelor and Master thesis supervision**
  Total 12 bachelor and 8 master theses.

Foreign Stays

- **BT Group, Pervasive ICT Research Centre, Ipswich, UK (2004-2006)**
- **Santa Fe Institute, Santa Fe, NM, USA (06-07/2005)**
- **Technion – Israel Institute of Technology, Haifa, Israel (08-10/2000)**

Patents

- Jakob, M. - Healing, A. - Saffre, F.: Quality based service selection in a peer to peer. European patent EP2027536 B1 / U.S. patent US8244857 B2. Granted: Jul 11, 2012.
- Saffre, F. - Healing, A. - Jakob, M.: Peer to peer reporting system on reputation of quality for service. European patent EP2033086 B1 / U.S. patent US8176170 B2. Uděleno: Feb 24, 2010.

Selected Publications

Articles in impacted journals:

- Hrncir, J. - Rovatsos, M. - Jakob, M. Ridesharing on Timetabled Transport Services: A Multiagent Planning Approach. In: *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations.* 2014. ISSN 1547-2442
- Vanek, O. - Jakob, M. - Hrstka, O. - Pechoucek, M. Agent-based model of maritime traffic in piracy-affected waters. In: *Transportation Research Part C: Emerging Technologies.* 2013, vol. 36, p. 157-176. ISSN 0968-090X.
- Jakob, M. - Pechoucek, M. - Cap, M. - Novak, P. - Vanek, O. Mixed-Reality Testbeds for Incremental Development of HART Applications. In: *IEEE Intelligent Systems.* 2012, vol. 27, no. 2, p. 19-25. ISSN 1541-1672.

Papers in the proceedings of international conferences:

- Egan, M. - Jakob, M.: A Profit-Aware Negotiation Mechanism for On-Demand Transport Services. In: *European Conference on Artificial Intelligence.* 2014. p. 273 - 278.
- Hrncir, J. - Zilecky, P. - Song, Q. - Jakob, M.: Speedups for Multi-Criteria Urban Bicycle Routing. In: *15th Workshop on Algorithmic Approaches for Transportation Modelling*, Optimization, and Systems. 2015, p. 16-28. ISBN 978-3-939897-99-6.
- Jakob, M. - Vaněk, O. - Hrstka, O. - Pěchouček, M.: Agents vs. Pirates: Multi-Agent Simulation and Optimization to Fight Maritime Piracy.

In: *Proceedings of the 11th International Conference on Autonomous Agents and Multiagent Systems*. County of Richland: IFAAMAS, 2012, vol. 1, p. 37-44. ISBN 978-0-9817381-2-3.

In total over 40 papers in the proceedings of international conferences and workshops.

Other Research Products

- **Urban Bicycle Route Planner (2015)**
  Web application prototype available from:
  `http://cykloplanovac.cz`.
- **Flexible moblity services testbed (2014)**
  Open-source software available from:
  `https://github.com/agents4its/mobilitytestbed`.
- **Multimodal transport network analyser (2013)**
  Web application prototype available from:
  `http://transportanalyser.com`.
- **AgentC maritime traffic analysis and simulation framework (2012)**
  Software. Transfered to U.S. Navy Research Lab for further development and use.

Service

Membership of conference programme committees: Intl. Conference on Autonomous Agents and Multiagent Systems (2011-2014), Intl. Conference on Practical Applications of Agents and Multi-Agent Systems (2011-2014), European Conference on Artificial Intelligence (2014), Intl. Conference on Prestigious Applications of Intelligent Systems (2014), Intl. Conference on Principles and Practice of Multi-Agent Systems (2011), IEEE Int. Conference on Intelligent Transportation Systems (2015)

Reviewing for journals: IEEE Transactions on Intelligent Transportation Systems, IEEE Transactions On Systems Man And Cybernetics Part A: Systems And Humans, Applied Artificial Intelligence.

Personal Data

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