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# Cycle-tourist network design

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**Abstract**

Among the most effective actions to promote functional cycling, i.e., cycling as a mean of transport, infrastructure design and planning are major topics. Much less attention has been dedicated to the design and deployment of bikeways devoted to recreational cycling, despite the role of cycle routes in promoting cycle tourism, and the effectiveness of cycle tourism in fostering sustainable and environmentally friendly economic growth, in addition to encouraging healthy life styles. In this paper we contribute to fill this gap: we propose a quantitative based methodology for designing a cycle-tourist network infrastructure intended to provide local administrators with a quantitative based decision support tool to optimally exploit the scarce public funding devoted to the project deployment. We consider as a case study the data of the Trebon region, in South Bohemia. Given the local points of attractions and a set of potential links which can be turned into cycle pathways against a little investment in addition to a set of links already fit for cyclists, a network of cycle routes that interconnects a set of pre selected gates must be designed, so that the total link refurbishment cost is budget compliant and the attractiveness of cycle itineraries from gate to gate supported by the infrastructure is maximized.

In previous studies we showed how to compute a resource-constrained optimal path from origin to destination, which maximizes a utility function related to the attractiveness of the arcs and nodes along the path. In a later work we generalized the problem to the case of multiple users with different utility functions that must share the same monetary budget. Building on these results, in this paper we propose a heuristic solution approach for the network design problem, where routes connecting several origin destination pairs have to be designed, yielding a connected infrastructure which allows for further itineraries. We exploit the ability of modern solvers to quickly find solutions to the single-pair single-user aforementioned case to generate a pool of promising paths from gate to gate, according to different preferences and constraints. In a second step, the network is built by solving a second combinatorial optimization problem which selects a path for each pair of gates from the pool, to yield a budget compliant connected infrastructure. Finally, a post optimization step deletes redundant links, if any.

The solution approach is validated by an experimental campaign performed on realistic data for the Trebon zone, in Southern Bohemia.



*Keywords:* Bicycle network design; cycle tourism; routing with profit; orienteering problem; heuristic;

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## 1. Introduction

Environmental concerns over pollution and climate change, which have been dominating the public debate in the last few months after the United Nations convention in Paris, bring to the forefront the discussion on how to promote sustainable economic growth and encourage soft mobility at the same time. Fostering cycle tourism provides an answer to both concerns. First, cycle tourism may activate a positive synergy towards functional cycling, i.e., cycling as a mean of transport, even in those countries without a well-established cycling culture that have experienced the automotive domination for years. Since regular cyclists are more willing to commute by bike than others, promoting cycle tourism and enlarging the cyclist community indirectly fosters the use of bike as a mean of transport, as the case of the Great Western Greenway in Ireland, described in Deenihan et al. (2013), suggests: created to attract visitors and to cater to recreational cycling, it increased the percentage of sustainable travel patterns of residents, school commuting by bike in particular. It has also been observed that, once a cycling infrastructure has been deployed, even if it was originally designed for leisure it often gets used for functional journeys by experienced cyclists. At the same time, these cycling facilities provide an opportunity to practice for first time cyclists and for those starting to cycle again as well. These people find a friendly and protected environment where they can gain or regain confidence with this mean of transport while having fun in complete safety, and are more likely to become potential utility cyclists afterward. Second, cycle tourism is an expanding sector in several European countries and represents an opportunity for economic growth in a sustainable and environmental friendly manner. Being able to attract cycle-tourists expands the regional economy by boosting small businesses run by local communities aimed at providing a different range of services to the tourists, varying from small scale lodging facilities to technical support for bikers, including regional food productions and all those activities related to the exploitation of local culture and traditions, as discussed in the final report of the European Project Cycle Cities (2014).

Whether intended for leisure or mobility needs, the level of cycling depends on the quality of available infrastructure, whose design methodologies still pose several challenges to the scientific community. In fact, decision makers are eager for reliable quantitative tools to support them when designing from scratch or when expanding a cycling network. A flourishing literature aims at defining the ideal characteristics of bikeways to be built along existing roads, taking into account traffic data, the geometrical shape of the roads, and the features of bicycles as means of transport (speed and safety distances), generalizing to bicycles the methodologies applied to vehicles, as discussed in detail, for example, in the Local Transport Note 2 (2008) report issued by the U. K. Department of Transport. Fewer are the studies that analyze the impact of infrastructure improvements on cycling mobility, such as Hamilton and Wichman (2015), or how to anticipate expected benefits in terms of traffic reduction and modal shift, such as Wardman et al. (2007). Although functional cycling network design is undoubtedly at the top of the agenda of local governments and planners, to our knowledge there is no assessed methodology for it. At the same time, the scarce literature on the design of leisure devoted infrastructures for cyclists usually disregards the hints coming from functional cycling, and tends to privilege the analysis of economical and societal impacts of the existing systems and their interrelations with the transportation network (see for example Lumsdon (2000) where the tourist transport system is discussed). On the contrary, we believe that a few issues are common to both fields with slightly different interpretations, such as continuity, attractiveness, safety, and societal and economical impacts of a cycling infrastructure, beside evaluation of user needs, as discussed hereafter.

Certainly, the **continuity** of cycle pathways is an important feature in both cases. Its lack is often questioned by urban cyclist and it strongly affects the perceived suitability of cycling as a transport mode of choice. In a similar way, a cycle route devoted to cycle tourists is appealing to a large community only provided that it ensures a certain quality standard throughout its way, from origin to destination, and connects all the local attractions in a seamless manner.

**Attractiveness** is another common issue. In case of recreational cycling, the leisure and attractiveness of cycle routes are obviously necessary requirements. The concept of attractiveness is related not only to the particular features of the pathway but it extends to the appeal of the points of interest reachable along the pathways and to the traversed landscape. In a more restricted interpretation, the positive impact of pathway attractiveness started to be recognized by academics and city planners also in case of cycleways intended to commuters within a urban environment, as reported in Lin and Liao (2014). Indeed, attractiveness turns out to be, beside safety and comfort, among the most influential factors that drive functional cyclist behavior, and it was selected as one of the attributes on which the quality index for functional cycling infrastructures proposed in Hulla and OHolleranb (2014) is based. Finally, promoting cycling as a mode of transport provides direct and indirect **economical benefits** since it decreases motorized traffic and improves population health and wellbeing. Besides, functional cyclists tend to shop locally, thus supporting the local economy as well. On the side of recreational cycling, local administrators finally got to acknowledge that providing bikeways that connect touristic spots is an effective strategy in promoting tourism-based sustainable growth and fostering the economy of regions that are not renowned touristic destinations but have all the assets required to please cycle tourists, i.e., beautiful landscapes, strong cultural traditions, and historical monuments all concentrated within a small area. Quite often, though, the areas that would qualify in terms of attractions and landscape miss an appropriate infrastructure. In fact, cycle tourism refers not only to tourists using bicycles as the main transportation mean to reach the tourist attractions; on the contrary, cycling is an integral part of the tourist experience and the level of satisfaction is largely influenced by the quality of the infrastructure. Bikers enjoy riding in a preserved natural environment, provided that it be equipped with adequate riding facilities. In particular, **safety** is an essential feature cycle tourists require even more than functional cyclists, so that existing links open to heavy vehicle transit do not qualify to be part of a cycle pathway, even if provided with a segregate lane, while functional cyclists may tolerate them over short lengths as part of their route. Foster et al. (2011) shows a negative correlation between leisure cycling and traffic volume: even though safety is a common concern among functional cyclists and recreational cyclists, its lack seems to affect cycle tourists much more than cycle commuters. This difference can be partially explained reminding the different experience level, on average, of leisure versus utility bikers, the latter being generally more comfortable mixing with motor traffic.

When designing a cycle infrastructure intended for leisure, an opportunity that meets sustainability concerns and budget constraints consists of reconditioning existing tracks and reserving these facilities to cycle tourists, besides exploiting the few existing roads with very light traffic in order to guarantee cycle paths continuity and to provide a connected and coherent network topology that makes the main points of attractions easily reachable along appealing itineraries. Potential links to be reconditioned include unpaved forest trails, gravel roads, canal towpaths, and even reconverted abandoned railway lines, all of which can be turned into properly paved and equipped cycle tracks at a moderate cost. Building from scratch a few, low-impact, small infrastructures (such as, for example, a wooden bridge crossing a creek that would connect existing tracks) is also a considered option. However, such choices should not be guided exclusively by the exploitation of redundant assets, as discussed in Downward and Lumsdom (2001); in common practice, studies on user needs ex ante are surrogated by a post-construction marketing campaign to promote the product. This is also the case for functional cycling. Indeed, a common feeling among utilitarian cyclists is that cyclists are very often an afterthought to the planning process as reported in Hulla and OHolleranb (2014): they complain that **user needs** are not taken into account at infrastructure deployment time. On the contrary, the potential users point of view must be accounted for from the beginning of the planning process, and this holds for both recreational and functional cycling; consultations with local cyclists should take place before planning, so that the design choices can mirror a plurality of user profiles. Since public funding devoted to these projects are usually limited, local administrators need reliable decision support tools to make best use of their spending capacity and optimally make selective choices exploiting all the available information.

In this study, we try to give our contribution to the field; we propose and discuss quantitative methodologies for optimally designing a recreational infrastructure meant to be used by cycle tourists by selecting a proper set of tracks to be reconditioned, taking into account budget constraints and user preferences; then, we apply our methodology to realistic data regarding the Trebon region in Southern Bohemia, Czech Republic. While most studies focus on a corridor structure that stretches from two extremes, we are concerned with a confined area, where several visitor attractions are located not far from each other, which the network should provide access to and mutually connect along itineraries fit for casual, recreational day cyclists. In particular, we envision a system where the access to the cycling network is provided through a limited set of gates: these are locations that are connected to the road network and to the local public transport network, whether bus or train, and are equipped with parking lots and renting facilities. To enhance the service, in a further perspective the gates could be served along a circular line by a shuttle service which could also be used to reposition rented bicycles. The cycling network should connect the gates to each other and to the most attractive spots by way of scenic pathways whose riding provides the maximum satisfaction to the potential users, according to their preferences. Moreover, the new infrastructure should exploit the existing tracks already fit for cyclists by considering each of them as an additional asset rather than taking all of them for granted without discretion.

More formally, the problem we face can be stated as follows: We assume that the following information has already been collected: i) the most sought after locations present in the area and the tracks that potentially connect them; ii) the locations that could act as gates and give access to the cycle network from the outside; iii) the utility functions of a predefined set of user classes, quantifying the reward experienced by the user when biking along a link or visiting a site; iv) the cost of refurbishing each potential link, including those already available. The problem consists of selecting the optimal set of links to be reconditioned and to be part of the network, so that, for each user class and for each origin-destination pair of gates each pair of gates is connected along an itinerary not longer than a given duration, the total budget available for reconditioning is not exceeded, and the sum of the attractiveness of the itineraries over the different user classes is maximized. Note that the first requirement guarantees that the whole network is connected.

The methodology developed in this study builds upon the results presented in previous EWGT conferences. In particular, in Cernà et al. (2014) we introduced the Most Attractive Cycle Tourist Path Problem (MACTPP) and we studied how to compute the most rewarding itinerary from origin to destination, subject to duration and budget constraints, with decreasing attractiveness at successive traversals of the same edge and node. Since MACTPP has strong ties with the Orienteering Problem (OP) (see Vansteenwegen et al. (2011)), we proposed a Mixed Integer Linear Programming (MILP) model that generalizes a model for the OP and which is easily solvable by commercial solvers for realistic instances. A follow up study Malucelli et al. (2015) generalizes MACTPP to several classes of users with different attractiveness functions that must share the same budget, and showed experimentally that using more information in the planning phase pays off in terms of potential attractiveness of the resulting infrastructure. So far, only itineraries for a single origin-destination pair were addressed. Building on these results, in this paper go a step further and we propose a heuristic solution approach for the entire network design problem, in which a set of itineraries is selected, each one connecting an origin-destination pair (a pair of gates), and then joined to yield a connected infrastructure linking all the gates that allows for further routes.

The solution approach is described in section 2. We exploit the ability of modern solvers of quickly solve MACTPP to generate a pool of promising paths, with different durations and refurbishment costs as we describe in 2.1. In a second step, the network is built by solving a second (new) MILP model, which selects a path for each user class and for each pair of gates, picking from the previous set of paths, to yield a budget compliant connected infrastructure that maximizes total attractiveness, as described in section 2.2. Finally, the network is refined according to the procedure presented in section 2.3. We apply the methodology to realistic data referring to the Trebon region in Southern Bohemia: the results of the computational campaign are discussed in section 3, then conclusions are drawn and future research directions are proposed.

## 2. A three-phase, MILP based, heuristic solution approach

In this section we provide the details of the three phases our solution approach is made of, namely path generation, path selection, and network post optimization. This decomposition is based on the assumption that the network that we envision is given by the union of the edges of the itinerary from gate to gate that we have selected as the most rewarding one, for each user and for each pair of gates, and whose duration is at most 1.5 times longer than the shortest path. If we knew the optimal network we would know the duration and the cost of the paths, from gate to gate, that are part of the final solution. However, those paths are unlikely to be the optimal ones, i.e., those maximizing the attractiveness given that duration and cost, since they have to meet the global budget constraint that links decisions taken locally for each pair of gates. Nevertheless, those paths are probably suboptimal ones. Therefore, we propose to generate optimal paths for different thresholds of duration and budget not greater than a guess of those allowed for each pair (step 1 of the approach), then pick into this set to generate a budget compliant network (step 2), and finally verify how the user would move along this network (potentially putting subpaths of the selected paths one after the other to yield new paths) and set those itineraries as the chosen paths, thus refining the network by getting rid of unconfirmed edges (step 3).

Having divided the problem into steps allows to exploit optimization methods at each decision phase, whereas the solution of the whole network design mathematical model in a single step is beyond the reach of state of the art solvers. This incremental approach allows flexibility into the implementation of the steps concerning both the methodology as well as the timeline of the realization. Indeed, the task related to each step could be accomplished by any other technique other than those proposed here; moreover, computing the network as the union of a set of paths allows for an incremental deployment, according to which the infrastructure is gradually realized step by step as investments proceed with capital availability, prioritizing those interventions that have the most promising returns.

### 2.1. Path Generation

As a first step, we build a set of candidate paths by generating itineraries that take into account user preferences for each user class and maximize the reward given a limited duration $T$ and budget $B$. To this aim we solve the optimization model for MACTPP introduced in Cernà et al. (2014) that we briefly recall hereafter for sake of completeness. The network of potential bike tracks is represented as a mixed graph $G = (N, A \cup E)$ where $N$ models the set of intersections and $E$ models the set of tracks connecting two adjacent intersections $i, j \in N,\ i < j$, while each arc in $A = \{(i, j), (j, i)\ \forall\, [i, j] \in E\}$ represents the action of traversing edge $[i, j]$ from $i$ to $j$ or vice-versa. For each arc, traveling time $t_{ij} > 0$ is known and it depends on length and slope of the track; itinerary duration can not exceed $T$. Reconditioning edge $[i, j]$ costs $c_{ij} \geq 0$ and the monetary budget is $B$. MACTPP searches for a (not necessarily elementary) path on $G$ from a given origin $s \in N$ to a given destination $t \in N$, for a given user class $u \in U = \{1, .., n_u\}$, maximizing the attractiveness. Attractiveness is defined on edges and nodes, and depends on the user class $u$. The following features hold: no traversal yields null reward, the reward at first and second traversal for each node and edge are problem data while reward is null from the third time onward. So far on recalling MACTPP.

In this study we use the MILP model for MACTPP presented in Cernà et al. (2014) as a black box and solve the problem several times, for several origin-destination pairs and parameters. Denote by $\Gamma = \{1, .., n_\Gamma\} \subseteq N$ the set of gates providing access to the network, and let $\Gamma^2$, indexed by $k \in \left\{1, .., (n_\Gamma - 1)\frac{n_\Gamma}{2}\right\}$, be the set of unordered pairs $(\gamma, \nu)$ with $\gamma,\ \nu \in \Gamma$. For each $u \in U$, and for each pair $k = (\gamma, \nu) \in \Gamma^2$ we consider the pair $(u, k)$ as a commodity in the set $C = U \times \Gamma^2$, and we compute a set of candidate itineraries $P(u, k)$ for each commodity by solving MACTPP with respect to different values of $T$ and $B$. Setting $T$ and $B$ so that the associated optimal path is likely to belong to the optimal solution is not straightforward, so a few tentative values are considered. For each pair $(\gamma, \nu)$, $T$ ranges from the the duration of the shortest path connecting $\gamma$ and $\nu$ to a multiple of this value, in order to produce a set of paths of very different durations which may satisfy the expectations of different types of users about the length of a one day trip itinerary. Regarding the budget, setting a threshold for all pairs is a tricky task for several reasons. First of all, due to zero cost edges the cost of the cheapest path may not be proportional to the distance, so that setting the budget according to the maximum duration $T$, i.e., $B$ would be a function of $T$, poses a question of feasibility since it is not guarantee that a path not longer than $T$ exists that costs no more than $B$. Furthermore, a second issue concerns the ratio between $B$ at path generation and the budget allowed for the whole network, say $B^N$. If the paths generated at step 1 are too expensive, step 2 will fail. A simplistic solution would be to set $B$ equal to a share of $B^N$; in case of equal share $B = \frac{B^N}{n_C}$ for all pairs, where $n_C$ is the number of commodities. However, it is very likely for several links in the final network to belong to more than one route, so they contribute to the share of each path but contribute only once to the cost. Therefore the sum of the budgets allocated to each commodity is likely to be quite greater than $B^N$. For this reason we propose to vary the budget at each MACTPP instance for a given commodity within a range whose lower bound is higher than the minimum cost required to connect any pair of gates, and the upper bound corresponds to a fraction of the cost of all the edges. This fraction may vary according to the percentage of zero cost edges, if any, present in a given instance which represent the existing infrastructure.

Once thresholds $T$ and $B$ have been set for each $k \in \Gamma^2$, MACTPP is solved for each such values to yield the set $P(u, k)$, the candidate paths for each pair of gates and user class. The reader can refer to Cernà et al. (2014) for more details on the model, and to Fischetti et al. (2007) for the Orienteering Problem of which our models are a generalization. Actually the ILP model we adopt here, whose formulation is not provided for conciseness sake, slightly differs from the one in Cernà et al. (2014) as it allows at most two traversals of the same edge.

### 2.2. Path Selection

We propose two slightly different ways of assembling the paths to build the network, and provide the mathematical models for both: the former selects one path per commodity, the latter one path per pair of gates, assuming that all users will follow the same itinerary when cycling from $\gamma$ to $\nu$.

Let us introduce some notation to present the models. Let $P = \bigcup_{u \in U, k \in \Gamma^2} P(u, k)$ be the set of all candidate paths, and let $\phi_p^{uk}$ denote the attractiveness of $p \in P(u, k)$. We associate a boolean variable $\pi_p^{uk} \in \{0, 1\}$ to each path $p \in P(u, k)$ and a boolean variable $z_{ij}$ to each edge $[ij]$. Let $\delta_{puk}^{ij}$ be the Kronecker symbol being 1 if edge $[ij]$ belongs to path $p \in P(u, k)$, and 0 otherwise. Let $n_C = |C|$ be the number of commodities, where $C = U \times \Gamma^2$, i.e., $n_C = n_u(n_\Gamma - 1)\frac{n_\Gamma}{2}$. Both models are made of three sets of constraints concerning coverage, budget, and logical implication. The first model $M1$ is given by (1–6): Constraints (2) ensure coverage, as they impose to select one itinerary for each commodity, i.e., one path from each set $P(u,k)$; Constraints (3) ensure that if at least one path using edge $[ij]$ is selected, then variable $z_{ij}$ is set to one, so that constraint (4) guarantees the monetary feasibility of the project. Constraints (3) are as many as the edges: they are a strong version of the $|P| \cdot |E|$ constraints $\pi_p^{uk}\delta_{puk}^{ij} \leq z_{ij}$, exploiting the fact that in $M1$ the number of commodities $n_C$ is an upper bound of the number of paths sharing an edge. Constraints (5 - 6) state that variables $z_{ij}$ and $\pi_p^{uk}$ are binary.

$$max \sum_{u\in U,k\in\Gamma^2} \sum_{p\in P(u,k)} \pi_p^{uk}\phi_p^{uk} \qquad \text{subject to:} \tag{1}$$

$$\sum_{p\in P(u,k)} \pi_p^{uk} = 1 \qquad \forall u \in U,\ k \in \Gamma^2 \tag{2}$$

$$\sum_{u\in U,k\in\Gamma^2} \sum_{p\in P(u,k)} (\pi_p^{uk}\delta_{pc}^{ij}) \leq z_{ij} n_C \qquad \forall\,[ij] \in E \tag{3}$$

$$\sum_{[ij]\in E} c_{ij} z_{ij} \leq B^N \tag{4}$$

$$z_{ij} \in \{0,1\} \qquad \forall [i,j] \in E \tag{5}$$

$$\pi_p^{uk} \in \{0,1\} \qquad \forall u \in U,\ k \in \Gamma^2 \tag{6}$$

The second model $M2$ selects one path for each pair of gates in $\Gamma^2$. It is obtained by way of some modifications of the first model. The objective function is (7), constraints (2) become (8), and constraints (3) are modified as in (9) with $n_{\Gamma^2} = (n_\Gamma - 1)\frac{n_\Gamma}{2}$. In order to ensure fairness and variety, we can add a new constraint (10) imposing that, for each $u \in U$, at least a fair share of paths among the $n_{\Gamma^2}$ requested ones belong to the sets $P(u,k)$, i.e. for example at least $\frac{n_{\Gamma^2}}{n_u+1}$ must be *optimal* according to the utility function of user $u$. Model $M2$ is made of (7-10) and (4-6).

$$max \sum_{p\in P} \left( \pi_p^{uk} \left( \sum_{u\in U} \phi_p^{uk} \right) \right) \qquad \text{subject to:} \tag{7}$$

$$\sum_{u\in U} \sum_{p\in P(u,k)} \pi_p^{uk} = 1 \qquad \forall k \in \Gamma^2 \tag{8}$$

$$\sum_{u\in U,k\in\Gamma^2} \sum_{p\in P(u,k)} (\pi_p^{uk}\delta_{pc}^{ij}) \leq z_{ij} n_{\Gamma^2} \qquad \forall\,[ij] \in E \tag{9}$$

$$\sum_{p\in P(u,k)} \sum_{k\in\Gamma^2} \pi_p^{uk} \geq \frac{n_{\Gamma^2}}{n_u + 1} \qquad \forall u \in U \tag{10}$$

### 2.3. Post optimization

In case of multi commodity network design, if the network has been obtained by assembling *candidate* paths associated to each commodity, it may happen that the actual itinerary followed by a certain commodity on the final network may not coincide with the chosen candidate one. To take this issue into account, we perform a post optimization phase. For each commodity, we compute the most rewarding path not longer than the duration of the longest candidate path for that commodity, considering only the edges of the network. The edges that have not been used by any commodity are deleted from the network.

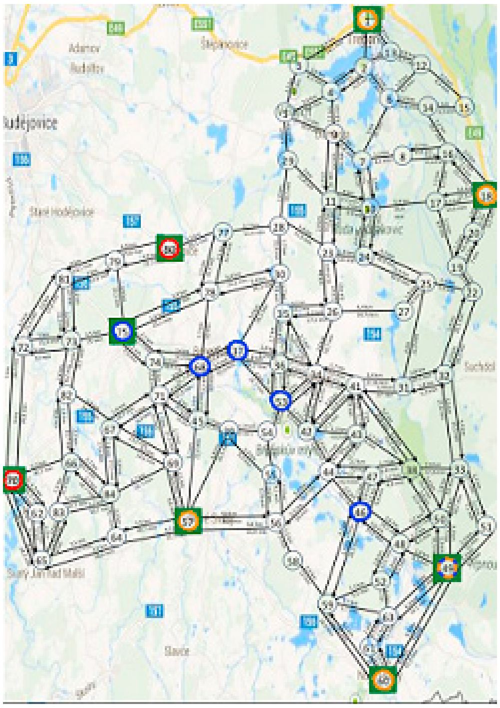

Figure 1. Graph $G$ overlapping the physical map of Trebon

## 3. Computational results

We exploited the data set used in Cernà et al. (2014) and Malucelli et al. (2015), representing the Trebon region. We briefly recall the data description provided in those papers. Graph $G$ is made of a set of candidate links, some of which require an investment to be reconditioned into cycle tracks while others are already fitting and can be used at zero cost. The former are unpaved roads or natural trails that are being used for off road cycling or hiking. The latter are minor rural paved roads with low vehicular traffic and fit for cycling. Nodes are PoIs or cross-roads. The resulting graph has 84 nodes and 146 edges, 86 of which at zero cost. Arcs traveling time is computed with respect to an average speed 18 km/h, and adjusted to take slopes into account. The cost for reconditioning depends on present condition and path length: the estimated cost per meter of a $3m$. wide path is 115 € per meter to turn it into an asphalt surface if starting from dirt road, 75 € per meter from gravel one.

Based on the opinion of local bikers, eight locations have been selected to operate as gates in this study, yielding $n_{\Gamma^2} = 28$ unordered pairs to act as origin and destination of the itineraries. Figure 1 depicts the abstract graph overlapping the physical map of the region. Gateways are marked as green squares and correspond to nodes $1, 18, 49, 75, 57, 60, 70, 80$. Moreover, nodes $49, 46, 53, 37, 68, 75$ are railway stops, nodes $49, 57, 60, 1, 18$ are bus stops: the former are blu circles, the latter orange ones. Bus and train both provide bike transport. Nodes 70 and 80, shown as red circles in Figure 1, have been proposed as gateways by local bikers, as they are main locations on the road network. Distance (km) and travel time (minutes) on the arcs are also reported in Figure 1.

We consider three user classes $U = \{1..3\}$, namely those fond of culture, of local food and traditions, and of nature and sports, thus yielding $n_C = 84$ commodities $(u, k)$. To account for users point of view, for each user class the related Points of Attractions (PoIs) in the area have been recorded and evaluated by teams of local bikers, scores for first and second traversal have been assigned, and the attractiveness of edges and nodes was computed based on the PoIs located there and on the category of interest, as described in previous works.

The MILP models associated to the three steps have been coded in AMPL and solved by ILOG Cplex 12.5 on a quad core laptop with i7 processor. Each run required less than a minute, usually just a few seconds. As we are dealing with a design problem to be solved off line, we consider this performance satisfactory.

Regarding the values of the $T$ and $B$ parameters used in step 1, for each pair $(\gamma, \nu)$ the value of $T$ varies in a range expressed in terms of a percentage of $\tau_{\gamma\nu}$, i.e., the duration of shortest path connecting $\gamma$ and $\nu$, from 100% to 150% in steps of 10%. Since the procedure is applied to each of the 28 pairs and the distance within each pair varies substantially from pair to pair, this procedure produces paths of very different duration even if the procedure in step 2 tends to select the paths with longest duration, which have higher reward. The budget threshold $B$ takes four different values that guarantee that a feasible solution exists at step 1 for all the values of $T$ and for all pairs, namely $B \in \left\{6 \cdot 10^5, 9 \cdot 10^5, 12 \cdot 10^5, 15 \cdot 10^5\right\}$. The lowest value is higher than the highest cost required to connect any pair of gates, whatever the duration, while the highest value is the cost of selecting on average 6.5 edges, or the first cheapest 16, or the 3 dearest ones among those needing to be paved and reconditioned.

In the following we compare the networks obtained by setting the monetary budget $B^N$ at two different values, as a fraction of the cost required by reconditioning all potential links, i.e., $13,523 \cdot 10^3$ euros, namely $B^N = B1 = 1,700 \cdot 10^3$ (about a tenth) and $B^N = B2 = 3,500 \cdot 10^3$ (about a fourth) euros. We present eight networks obtained by combining the two model options (M1 and M2) with the budgets $B1$ and $B2$, and applying post optimization to each of the four networks (post optimization data are denoted by *). In our instances the fairness constraint (10) is always redundant, so we can not discuss its impact. In all maps, edges underlined in black are those with positive cost and colors are associated to the number of commodities that share the same edge, as in the legend of each map.

Table 1 reports the results before and after post optimization for each setting. Column 1 reports the settings, i.e., the model-budget combination; columns 2-4 report reward, number of edges and number of zero cost edges before step 3; columns 5-7 report the same data after step 3. The solutions are visualized in Figure 2 and 3.
As expected, before post optimization a higher budget allows for a higher reward for both models and almost proportionally, i.e., reward increases as much as the budget does, as does the number of non zero cost edges. Moreover, given the same budget, model $M1$ provides a slightly higher reward than model $M2$. Indeed, $M1$ can be seen as a relaxation of $M2$ since $M2$ allows a single itinerary for each pair of gates while $M1$ selects a potentially different itinerary for each user class. For tight budgets, as $B1$ is, this difference is limited but as a higher budget allows for more choices the difference becomes tangible.

Table 1. Reward and edges before and after (*) post optimization for the four settings.

| Setting | Reward | Edges | 0 cost edges | Reward* | Edges* | 0 cost edges* |
|---|---|---|---|---|---|---|
| $M1B1$ | 13972 | 97 | 86 | 20604 | 82 | 71 |
| $M1B2$ | 21417 | 106 | 86 | 22584 | 95 | 75 |
| $M2B1$ | 13513 | 97 | 86 | 20565 | 80 | 69 |
| $M2B2$ | 19793 | 107 | 86 | 22900 | 94 | 73 |

Figure 2 and 3 show the network topology before and after step 3 for model $M1$ and model $M2$, respectively.

Regarding the impact of step 3, note that before post optimization all the 86 zero cost links are present in each network, while after the post optimization a noticeable percentage of these links is dropped. However, comparing the maps before and after step 3 depicted in Figures 2 and 3, note that all the non zero cost edges that were selected at step 2 are confirmed after step 3. Nevertheless, reward increases after post optimization since it is not computed with respect to the selected candidate paths but to the way users will move on the network, following the best available itinerary on the current infrastructure which may be better than the selected candidate one. Indeed, by mixing edges belonging to different selected candidate paths, new itineraries that have not been generated at step 1 become available and can even be more rewarding than those selected. In such a case they might use more budget than allowed at step 1, and take advantage of sharing some edges with other itineraries to keep the network budget compliant. If the budget is as high as $B2$, the reward increase due to post optimization is limited (about 5%), while if budget is low as $B1$ the reward increases substantially and it is slightly lower than that achieved with budget $B2$.

The proposed methodology is a heuristic method since decomposes the problem into stages and solves one at a time without feedback. Nevertheless, it seems to be quite effective since it exploits the available assets, i.e., the zero cost links, being able to select among them which are useful and which are not by exploiting the data on the user preferences, rather than simply expanding the existing infrastructure without a comprehensive vision.

**Conclusions and work in progress** All decisions taken at designing and deploying cycling infrastructures must be based on a previous detailed analysis of user needs and preferences, to ensure that the intended targets will be achieved.

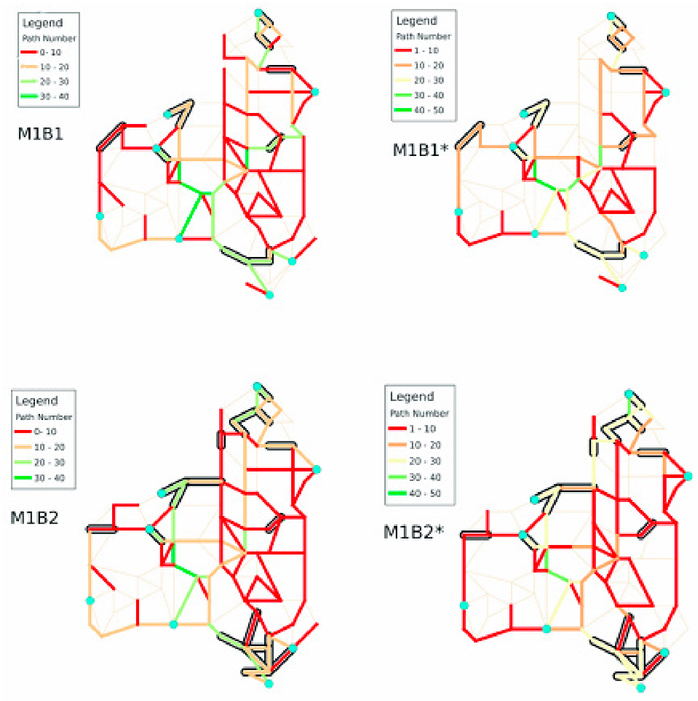


Figure 2. Maps for model $M1$

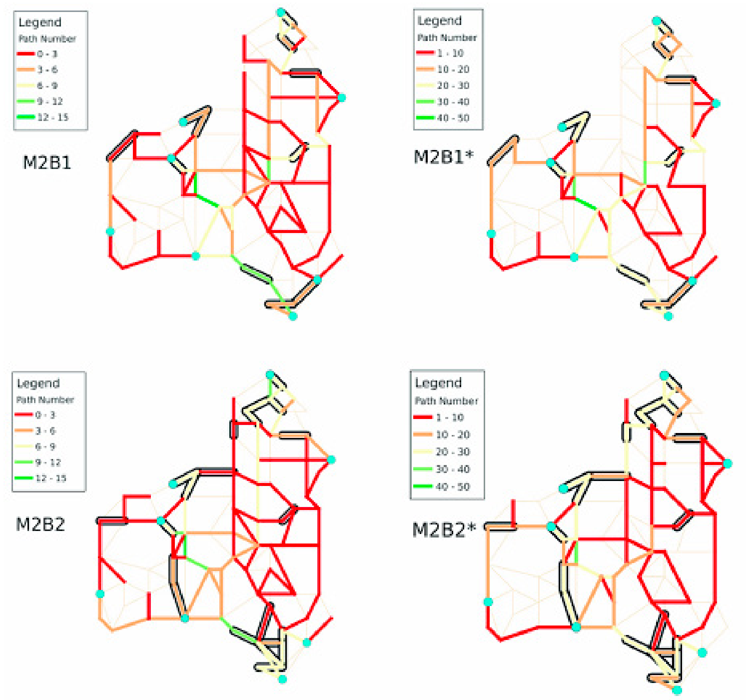


Figure 3. Maps for model $M2$

In case of recreational cycling the main goal is to attract cycle tourists to foster sustainable economic growth. Several case studies also suggest that an increased level of cycle based mobility of residents is likely to be observed following leisure-intended infrastructure deployment. To take these issues into account we exploited a quantitative description of the attractiveness of the potential links and junctions of the cycle network to consider the preferences of different user profiles, and proposed to use a utility function that decreases after the first traversal. We stressed the need for a design phase that considers the entire network as a whole but allows for incremental deployment. We proposed to build the network putting together itineraries connecting different pairs of gates. Gates were selected taking into account the interconnection with other means of transport. For each pair of gates and user profile a set of promising paths have been generated, a few have been selected to be assembled to yield a first network which is refined in a post optimization phase; different optimization models have been used to tackle each step of this process. The results show the effectiveness of the methodology even though, in our opinion, there are not yet assessed criteria according to which the resulting network should be evaluated in case of recreational cycling. Therefore, we adopted some criteria currently used to evaluate the quality of an infrastructure devoted to functional cycling. Attractiveness has been used as the objective function in all our models and the values of the attractiveness functions have been devised, as in previous works, to take into account different user profiles. The process is general enough to be adapted to consider whatever stakeholder, and the marginal attractiveness is decreasing for traversals from the first onward, to mirror user perceptions. The network continuity and connectivity is guaranteed by the methodology that builds the network by assembling paths from origin to destination. Safety is also guaranteed by considering either tracks that will be reserved to cyclists or minor rural roads with low traffic volumes. Including a few locations among the gates corresponding to small towns provides a connection by cycle routes between them that will encourage functional cycling of residents. Apart from these criteria, others more oriented to recreational cycling could be taken into account such as, for example, the variety of itineraries that result as possible detours from the main path within the maximum duration. We believe that this is a promising line of research and these hints are currently under study.

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