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Design of bicycling suitability maps for hilly cities

Lino Tralhao PhD
Researcher, INESC-Coimbra, Coimbra, Portugal

Nuno Sousa MSc, PhD
Invited Assistant Professor, Universidade Aberta, Lisbon, Portugal; Researcher, INESC-Coimbra, Coimbra, Portugal

Nuno Ribeiro MEng
Research collaborator, INESC-Coimbra, Coimbra, Portugal

João Coutinho-Rodrigues MSc, PhD
Full Professor of Civil Engineering and Researcher, INESC-Coimbra, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal

Sustainability worries related to the intensive use of energy by automobiles and traffic congestion issues have encouraged decision makers to look for alternative solutions, leading to an emerging shift towards soft/active transport modes. The bicycle, a very efficient mode of transport, is a soft travel mode that can be adopted in most cities, contributing to urban sustainability given the associated environmental, economic and social advantages. Cycling, however, also has its deterrents. Among these, it is recognised that slopes play an important role in influencing the choice for this mode of travel. The purpose of this paper is to present methods to analyse a hilly city's suitability for cycling, in what concerns relief, with the aim of identifying locations for implementation of hard aid devices that restore connectivity between most parts, or even the whole, of the city. The methodology proposed makes use of appropriate service areas. Geographical information systems technology was used to implement the methodology and the approach is demonstrated with a case study for the city of Coimbra, Portugal. This combined approach helps decision makers to plan the city in a sustainable way.

Notation

g	acceleration due to gravity
i	slope class number
M	man–machine mass
N	number of slope classes
P_a	power related to acceleration (e.g. for kinetic energy reposition after a stop)
P_d	power dissipated given the aerodynamic drag
P_g	power related to gravitational energy
P_r	power dissipated given the rolling resistance
s	gradient (slope)
t	travel time
v	bicycle velocity (horizontal component)
W	power at the pedal (human effort)
w_i	weight for route components of class i
η_m	bicycle mechanical efficiency
$\sum_j l_j^{(i)}$	length of class i components of route

1. Introduction

The post-war rise of automotive transport, fuelled by the abundance of cheap oil and favourable public policies, has ultimately led to urban sprawl, inefficiencies related to traffic congestion and energy consumption, and environmental concerns (Lefèvre, 2009). Lately these issues have become central to transport policy makers, as it is becoming ever more evident that the current state of affairs may not be sustainable in the long term (Kenworthy, 2008). The bicycle is a means of transport that can be adopted in most cities, which combines the readiness to use of the automobile with high efficiency, low congestion (one bicycle being roughly equal to 0·23 cars on road sections (Wang *et al.*, 2008)), health benefits (Meschika, 2012; Woodcock *et al.*, 2007) and quickness of travel for short distances (it is competitive with the automobiles up to 5 km (Dekoster and Schollaert, 1999).

These advantages have been noticed by policy makers, who have undertaken initiatives to foster bicycle use during recent decades in many cities around the world, especially in Europe (e.g. see Bypad, 2008). In tandem with this, research has been carried out to ascertain what factors influence a person's decision to ride a bicycle and what determines their route choices (Broach *et al.*, 2012; Parkin and Koorey, 2012; Parkin *et al.*, 2007, 2008; Rietveld and Daniel, 2004; Wardman *et al.*, 2007). Models were also devised to plan for bicycle paths, so as to optimise their attractiveness to cyclists (Suzuki *et al.*, 2012). These combined efforts, coupled with bicycle publicity broadcasts, have met with moderate to considerable success in increasing the share of the bicycle transport mode (Cervero *et al.*, 2012; Pucher and Buehler, 2008; Pucher *et al.*, 1999, 2011) and have caught the eye of decision makers in other cities and countries. Reproducing this success, however, requires planning, not only for economic reasons, but mostly because there exist a number of situations that act as a deterrent to cycling.

One of these deterrents is relief, which is known to have a strong negative impact on the propensity to use the bicycle for daily trips (Parkin *et al.*, 2008; Rietveld and Daniel, 2004). A study of cyclability should therefore include a relief component, especially if the city is hilly. This is a relevant issue because many cities (e.g. old European cities) were built on hills for military reasons. It is the purpose of this research to present a methodology that will enable decision makers to evaluate the topographic suitability of a city for cycling and to identify possible improvements to it. Although the issue is recognised as an important one, the related literature is, to the best of the authors' knowledge, scarce. This research is intended to cover some of this ground by proposing a systematic way to take the relief effect into account. The results generated by the methodology can then be plugged into existing models for bicycle path or circuit planning purposes.

The methodology presented herein comprises four stages

(*a*) classification of the city's streets network with respect to slope and length
(*b*) cyclability analysis
(*c*) cycling permeability analysis
(*d*) identification of possible locations for mechanical aid devices.

In the classification stage a geographical information system (GIS) of the city is used to classify arcs of the streets network according to slopes. This will form the basis of the subsequent analysis and is carried out in Section 2, together with the cyclability analysis, in the context of a case study – the hilly city of Coimbra, Portugal (see Figure 1, which illustrates one of the city's hills). Coimbra is an old, mid-sized city, with a population of about 150 000 inhabitants, of which around 37 000 are students.

In the permeability analysis, appropriate service areas for bicycle use are obtained in GIS. Having these areas makes it possible to identify disconnections in the network due to relief and how to overcome them. This is done in Section 3. Section 4 discusses the location of hard aid devices, the use of which would contribute to overcome disconnections in the cycling network, thus improving the city's overall cyclability. In Section 5, results for Coimbra are rounded up and a cycling circuit is presented, which exemplifies how the outcome of the proposed methodology can be useful as a basis for broader studies. Section 6 highlights a peculiar situation relating to the case study, showing this as an example of how to fine-tune the methodologies to deal with specific aspects of a particular city. Finally, the conclusions and prospects for the future are presented in Section 7. This research makes use of Esri ArcGIS Desktop and its extension, the NA.

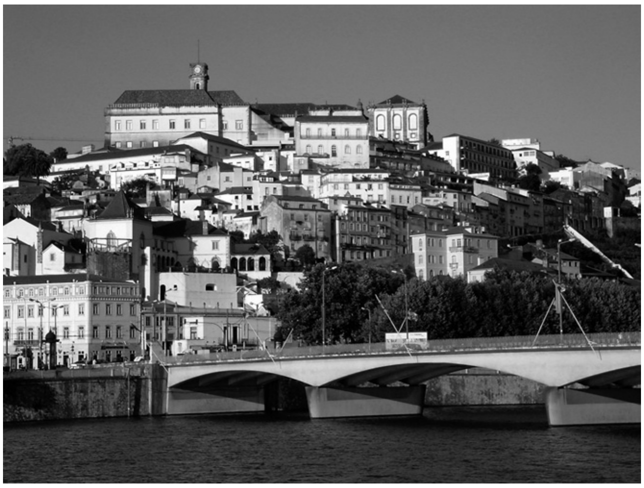

Figure 1. City of Coimbra – University Hill

It should be noted that the illustrative case study dealt mainly with the core of the city of Coimbra (designated as 'study area' below), with a particular emphasis on the part of the city eastwards from the Mondego River, which is where most of the population lives and works.

2. Network GIS modelling

As mentioned earlier, relief is an important issue when riding a bicycle, thus conditioning its massive use as a transportation mode. Slopes (or grades) greater than 5% are undesirable because climbing the ascents is difficult for many cyclists (Aashto, 1999, 2012), while steep descents hamper cyclists' speed control. As an example of climbing difficulty, consider a path of 7% slope. Such an incline is, on average, done at a speed of 3·21 m/s and power output at the pedal of 261 W. These values are presented in Parkin and Rotherham (2010), based on statistical (regression) work, and on the well-known (physics) formula

$$1.\quad W = \frac{1}{\eta_\mathrm{m}}(P_\mathrm{r} + P_\mathrm{d} + P_\mathrm{a} + P_\mathrm{g})$$

where W is the power at the pedal (human effort), η_m is the bicycle mechanical efficiency, $P_\mathrm{r} + P_\mathrm{d}$ is the power dissipated given, respectively, the rolling resistance and the aerodynamic drag, P_a relates to acceleration (e.g. for kinetic energy reposition after a stop) and P_g, the most important component in this work, is the power related to gravitational energy

$$2.\quad P_\mathrm{g} = M\boldsymbol{g}vs$$

where M is the man–machine mass, $\boldsymbol{g}$ is acceleration due to gravity, v is the bike velocity (more precisely, the horizontal component of it) and s is the gradient (slope). Considering $M = 95$ kg, at 7% slope the associated climbing power is $P_g = 209$ W, which accounts for a staggering 84% of the power at the pedal, according to Equation 1.

Regardless of the numbers, in practice human perception of the effort is also important. Because of this, both Austroads and the American Association of State Highway and Transportation Officials (Aashto) have proposed desirable slopes of paths for ease of cycling (Aashto, 1999, 2012; Austroads, 2009). The Aashto gives guidance on slopes of paths and respective acceptable lengths, as shown in Table 1.

The first task is therefore to classify the network arcs, with respect to slope and length. In the ArcGIS environment, a street network is modelled as follows: the arc between any two nodes (crossings), A and B, is modelled as a polyline (piecewise linear curve). Only the sequence of vertex coordinates (three coordinates for each vertex in three dimensions) of the polyline is stored. The first vertex of the sequence is called 'From', and the last vertex 'To'. Thus, for each arc, two directions exist: 'From–to' (the 'reference' direction) and 'To–from', which means that the network is in fact a directed network. Although most streets have approximately constant slopes throughout their length, in some cases this is not the case. As such, and in the present methodology, each arc is decomposed with respect to its reference direction into three types of segments: ascending, descending and flat segments. Since slope is constant in each of the segments, it is easily seen that, given Equation 2, segments of each type can be aggregated in only one combined part, having as length the sum of the lengths of its components, and as slope the average of the slopes of its segments, weighted by their horizontal projections lengths. Thus, each arc can be characterised by (l_{up}, s_{up}), (l_{down}, s_{down}) and l_0 (flat length), where l_{up} (l_{down}) are the sums of the ascending (descending) segments lengths, and s_{up} (s_{down}) are the averages of ascending (descending) slopes, weighted by their respective horizontal projection lengths. The arc length corresponds to $l_{\text{up}} + l_{\text{down}} + l_0$.

Slope: %	Acceptable length: m
5–6	240
7	120
8	90
9	60
10	30
11+	15

Table 1. Desirable uphill gradients for ease of cycling (Aashto, 1999)

Note that everything that is *up* in the 'From–to' direction becomes *down* in the 'To–from' direction, and vice-versa. All these quantities were evaluated using an auxiliary (Python) script implemented for this purpose and stored in associated tables. (In GIS objects characteristics/attributes are stored in tables; usually sets of objects with the same geometry and attributes have an associated table.)

An arc for which (s_{up}, s_{down}) $\leq$ 5% is defined as *strictly cyclable*, that is, cyclable in both directions regardless of length. It is *weakly cyclable* if it has a slope (up or down) higher than 5% but is nevertheless cyclable according to the Aashto table in at least one direction. If both the ascents and descents of a path are short enough, or if the path has a wavy profile, such a path would be easier for the cyclist to ride (even if overall the path is an ascent) due to the speed gained from downslopes. This issue may become important in borderline cases, particularly in slopes around 6%, which could warrant some sort of supplementary treatment. However the vast majority of the paths do not have such a profile, which is why the arc characterisation mentioned above seems like a reasonable enough approximation.

In Figure 2 a map of the network is presented. The arc greyscale tone corresponds to a GIS generated colour code and depends on $\max\{s_{\text{up}}, s_{\text{down}}\}$. This is usually the value implied when an arc is referred to as having x% slope. From the figure, some strictly cyclable zones can be readily identified. These are characterised by dominance of 0–5% arcs over large areas. Other parts of the city have weakly cyclable arcs, but it is not easily seen whether those arcs can link important zones. An inspection reveals that approximately 53% of the network (% of length) is cyclable. This includes isolated arcs, but leaves aside weakly cyclable ones (12% of the network). The remaining arcs make up 35% of the network and are non-cyclable, in the sense that they cannot be totally traversed in at least one direction (according to the Aashto table).

A note must be made here: adjacent arcs of 5–11% slope that are nevertheless cyclable may raise a chain problem. That is to say, while each of them may be cyclable per se, if two or more lie in succession, l_{up} of the path composed by those adjacent arcs may exceed Aashto cyclability bounds. This issue is addressed below where it was found to be relevant.

3. Network permeability

A given network zone is considered permeable to cycling if it allows the travelling by bicycle between any two of its points, back and forth. In the context of this research, the concept revolves around allowing the cyclist long trips (e.g. commuting), covering a great part (or even the whole) of the study area. In the case of a hilly city, it is likely that aid devices will prove necessary. Thus cyclability, as defined in Section 2, is not

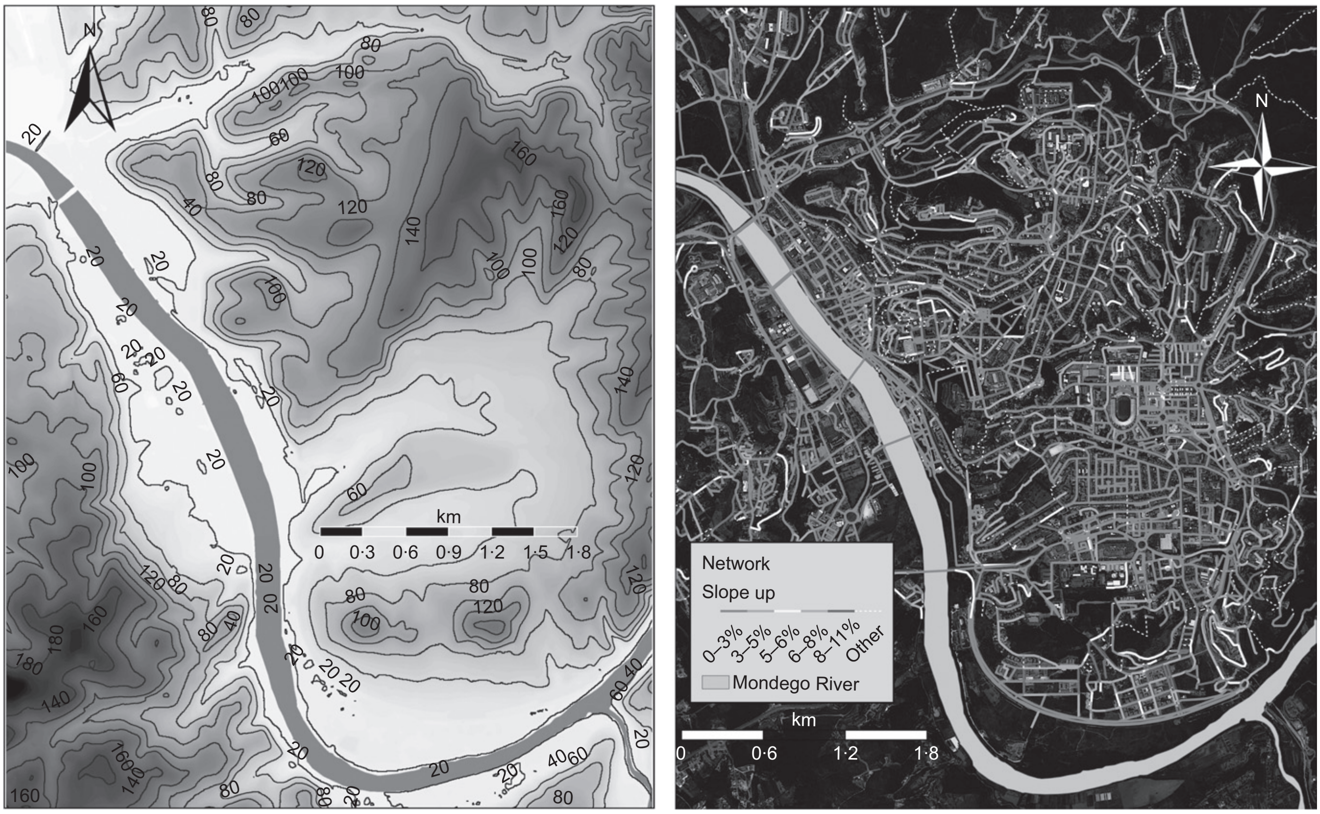

Figure 2. Topography of Coimbra, and cyclability of its urban network

enough for finding permeable zones. In fact, an arc (or small set thereof) may be cyclable but be surrounded by non-cyclable arcs, making its surroundings non-permeable.

Enlarging a hilly city's permeable zones naturally gives rise to the problem of locating aid devices so as to minimise their number, as well as their lengths. Also, as mentioned in Pucher (1997), it might be useful to consider a bicycling circuit within the study area, which is cyclable in both directions. In this way, to move between any two locations in the city, a cyclist could (*a*) ride towards the circuit, (*b*) traverse part of it, (*c*) exit it towards their destination. This circuit should be particularly bike-friendly and include most of the aforementioned devices. Another relevant aspect related to the circuit is that it should pass at the top-most and bottom-most spots of the study area (or at least close to them). The idea is that, apart from col (saddle) situations, and as long as there are no excessive descending slopes, all the points of the study area are accessible from the top-most spot. Also, as the bottom-most spot is accessible from all the others (with the aforementioned exceptions) and connects, by way of a circuit, the top-most, a significant part of the study area points become connected as well. This is what happened in the case study, with a few exceptions, the most important one being the hill where university campus I sits (old university, Unesco World Heritage Site – Zone 2, see Figure 3).

The issues raised in the two previous paragraphs are taken into account in the methodology proposed here for finding the permeable zones. Before addressing this, it is convenient to explain briefly some relevant concepts relating to the ArcGIS extension, the network analyst (NA). The latter is meant for dealing with networks, can be programmed so as to assign impedances (e.g. length, time, etc.) to network arcs and allows parameters to be defined prior to runtime. It also allows forbidding (*restrict*) arcs with certain characteristics, here usually slopes, in one or both directions, and was programmed/parameterised for this purpose. In short, the NA allows the analysis of specific network configurations/parameterisations, and can perform several types of studies over them, such as routing (i.e. finding least impedance paths) and the determination of service areas (SAs), the latter in fact being the central issue of the proposed methodology. Without going into details, consider the network portion that is reachable starting (*away*) from one point, or set of points taken simultaneously (the 'facility'). This resembles something like one or more trees, where each branch ends where a restricted arc is found for the configuration/parameterisation at hand. Facility points are the roots of these trees. The SA is the area obtained connecting those 'ends' by line segments, generating polygons. These polygons engulf areas in between tree arcs, but there is an option, which is always used in this research, to snip the polygons (*Trim Polygon*), so as to remove from them parts more than a certain distance away from the tree arcs. The resulting SA is thus an area made out of points up to a certain distance from the tree arcs (an area up to a certain distance from an object is called a *buffer*). Tree branches may eventually end before finding a restricted arc because a maximum impedance may be assigned for paths (*Default Break*). All the above refers to *away* service areas (i.e. 'where can you go, starting from facility'), but it also applies to *toward* service areas (i.e. SA determined in the opposite direction, towards the facility).

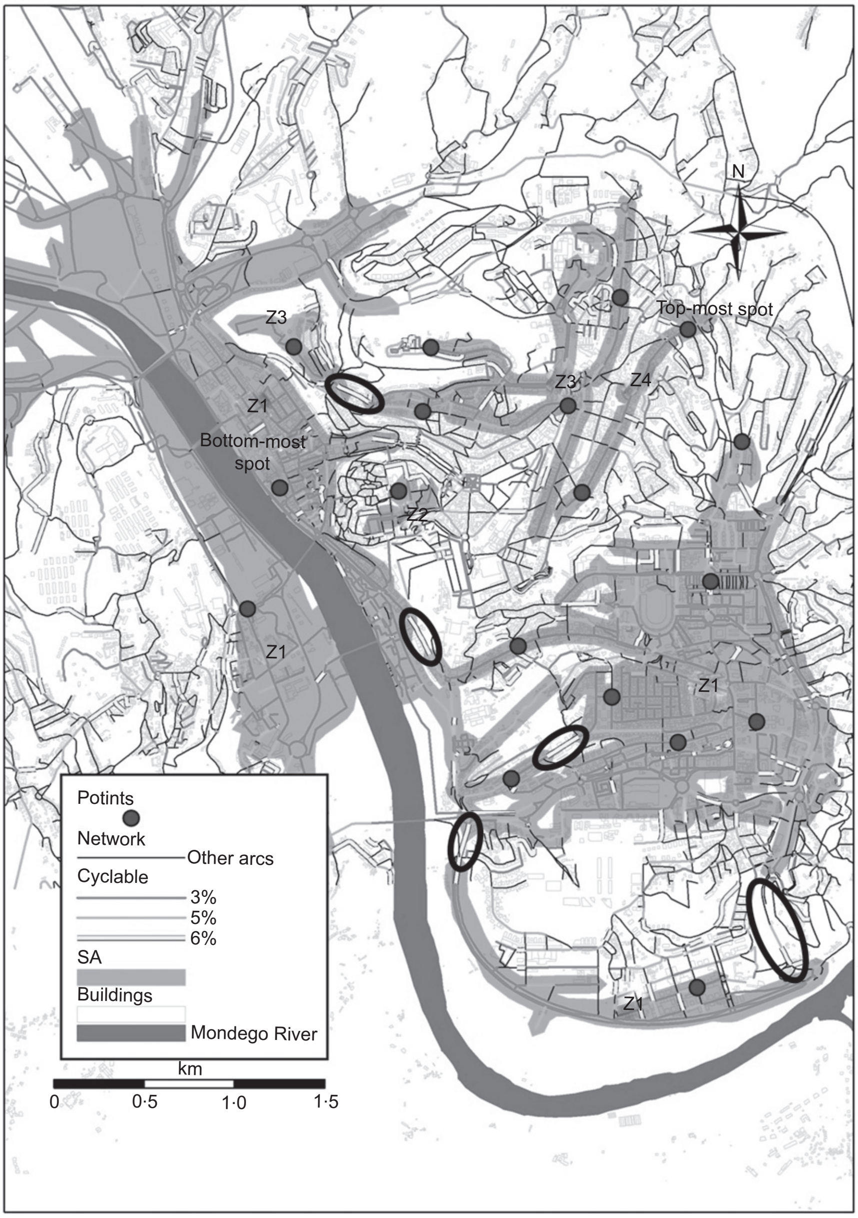

Figure 3. Set of points SA – disconnections

The methodology for finding the permeable zones consists of four steps, which are now described. In the first step a relief analysis of the study area is carried out, so as to identify a set of points that is representative of the study area. These points are usually located at plateau and/or ridge zones, but also at the lower zones of the study area. The set of plateau points selected for the case study is represented in Figure 3. The highest point of the study area should be in the set, or near a point of the set. The same applies to the lower point.

In the second step, the network is configured/parameterised (in the context of the *Network Analyst*) such that all arcs not strictly cyclable are restricted. Arcs not suitable for cycling (some bridges and speedways) are also restricted.

In the third step, the service area (SA) relative to the set of points above is obtained. This was done considering a *Default Break* that is very high (infinite in theory, enough kilometres in practice). In what concerns the buffer to be used, a compromise solution is convenient, between graphical visibility and visualisation of disconnections between the sub-SA generated (see shaded areas in Figure 3). In the case study a 50 m buffer was used, which will allow, to some approximation, the determination of the populations of the areas involved. The SA is represented in Figure 3.

Alongside the service areas, Figure 3 also displays borderline arcs with 5% < (s_{up}, s_{down}) ≤ 6% and (l_{up}, l_{down}) ≤ 240 m, in white. Because of their relevance for connection of zones, some of these arcs are potential candidates for infrastructural improvements. That is the case of the four left-most paths circled in black in Figure 3. These paths are important for connecting several zones and do not form chains. From inspection of the service areas and 5–6% paths, it can be seen that a significant portion of the southern part of the city and riverside can made permeable (zone Z1, 'downtown'). Note that it is irrelevant whether the SA is *away* or *towards* because non-restricted arcs are strictly cyclable.

Since the top-most and bottom-most spots are in the obtained SA, it is clear that, aside from the aforementioned col zones and excessive slopes, if it were somehow possible to 'fill-in' the existent disconnections, the whole, or at least a great deal, of the study area would become permeable. Thus, and in the last step of the permeability study, a detailed analysis of the arcs sitting at disconnections of the SA was made.

Finding directed paths connecting two sub-SAs can be done in a systematic way as follows. Since all arcs in a sub-SA are strictly cyclable, use the NA routing option and consider two points, X and Y, each one in a sub-SA. Forbid all arcs with (s_{up}, l_{up}) outside the Aashto table and those with $s_{\text{down}} > 11\%$. Then consider classes of slopes, for example 0–5%, 5–6%, 6–8%, 8–11% (up), ≤ 11% (down), 0%, and find the shortest routes from X to Y, and from Y to X, using the impedance function

$$w_1 \sum_j l_j^{(1)} + w_2 \sum_j l_j^{(2)} + \cdots + w_N \sum_j l_j^{(N)} \tag{3}$$

where N is the number of classes, w_i is the weight for route components of class i and $\sum_j l_j^{(i)}$ is the length of class i components of the route (may be zero). The set of weights works as a filter because relatively lower weights increase the preference for components of their classes. This property may be used to find 0–6% connections or to try to avoid the chain problem (higher weights help in that respect). If this procedure finds two paths, one for each direction, between two sub-SAs, a connection between those sub-SAs is then established. Eventually all of the zone sitting between them also gets connected, except if there are hills, cols or excessive downhill slopes in that zone (which is not the case in general). This procedure can be generalised considering several points in each sub-SA, located where these sub-SAs come the closest to each other. The various routes thus obtained can then be used as feedstock for a more detailed engineering heuristic analysis, which, should it be necessary to intervene (e.g. pavement improvement or device placement – see next section), will ultimately select a solution for implementation.

The above procedure made it possible to find a connection to the southernmost sub-SA (see Figure 5 bottom). This sub-SA can be reached by way of a west-side two-way connection next to the river and also (in the north–south direction only), by way of a path in its east side (rightmost black circle in Figure 3). The latter allowed the inclusion in the permeable zone of a neighbourhood next to it.

It was, however, not possible to find any connections between three zones, Z2, Z3 and Z4 ('uptown'), which clearly stand out as disconnected regions. This makes it clear that there is no way to link the four cyclable zones, as it is not possible to circulate both ways without the aid of mechanical devices. Those disconnections should thus be solved resorting to aid devices and finding appropriate locations for these is the subject of next section. For the case study, three locations were found, which are (see Figure 5, left to right): device 1, Z1–Z3; device 2, Z3–Z4; device 3, Z1–Z4. Zone Z2 has details of its own and will be considered in more detail in another section. Of these devices, only device 3 cannot be done without, because it climbs to the study zone's top-most point. Devices 1 and 2 do not alter the permeable zone but spare cyclists very long detours.

The SA serves a population of around 37 000 inhabitants, out of a total of 60 000 living in the study area. Most of these, 26 000, live in Z1, disconnected from the 11 000 of Z3 and Z4.

4. Possible location of hard aid devices

Aid devices can be, for example, elevators, funiculars, stairways/ramps, or tunnels, even though the latter are not the focus of this work. Figure 4 illustrates two types of aid devices (Figure 4(b) shows an elevator and Figure 4(a) shows a cyclocable – see it in action at https://www.youtube.com/watch?v=JtB8DX70ihM).

In choosing device locations, priority should be given to overcoming as high a slope as possible (this usually implies short lengths). One way to achieve this consists in trying to use already existing arcs, using the routing option of the NA and a technique similar to the one of Section 3 for finding connecting paths; the impedance function consisting now of a convex combination of $1/s_{up}$ and $L = l_{up} + l_{down} + l_0$ (for s_{up} values close to zero, artificial values can be assigned to $1/s_{up}$). Another way, which is necessary when the connecting arcs are non-existent, is to choose a new path, independent of the existing network. Like the previous approach, choosing this path is depends on the details of the location at hand. The first strategy was followed for obtaining the locations for devices 2 and 3, whereas the second one was used for device 1. Naturally, other criteria could be considered, eventually leading to different locations for the devices. Also, more devices (other than just the three presented) could also be considered, so as to reduce distances even further.

5. A possible main bicycling circuit

Another motive for preferring three devices in the case study is that their alignment clearly suggests the ring-like, fully cyclable, bicycle circuit of Pucher (1997). The devices would make up part of its north section. A possible circuit is presented in Figure 5.

This circuit's main characteristic is that it can be cycled in both directions. Thus, the SA corresponding to the circuit is the SA of any point of the circuit (the SA could also be obtained from the circuit itself). Furthermore, the SA corresponding to the circuit will correspond to the permeable zone of the area under study. Unfortunately, the chain problem makes it difficult to obtain that SA exactly. It is, however, possible to obtain a 'minimal permeability zone' by opening directed arcs with $s_{up} \leq 5\%$ and $s_{down} \leq 11\%$ (besides the ones in the circuit, as well as those connecting sub-SA). The resulting SA, obtained from the circuit point circled in black, is presented in Figure 5 (top). Enabling all directed arcs with (l_{up}, s_{up}) respecting the Aashto table and $s_{down} \leq 11\%$ a 'maximal permeability zone' is obtained, which, interestingly, does not differ significantly from the minimal area (hence not presented).

At the network level, the aid device has a travel time, t, associated to it. Thus, to model devices as network arcs (in a way that is consistent with other arcs – see Section 2), flat arcs with equivalent length $l_0 = vt$ were used. Any positive cycling speed v can be assigned (6 m/s was used).

For device 2 the streets are wide enough to accommodate a descending lane; for the two other devices the descending paths are separate, but also part of the circuit.

The circuit includes two already existing bike paths (although they are in need of improvements). There are not many alternative paths for the circuit in the north, south and east sectors of it. This is not the case for its west sector (mainly north-west), which crosses the centre of the city and warrants a more thorough study. This is, however, outside the focus of this paper,

(a) (b)

Figure 4. Hard aid devices: (a) cyclocable; (b) elevator

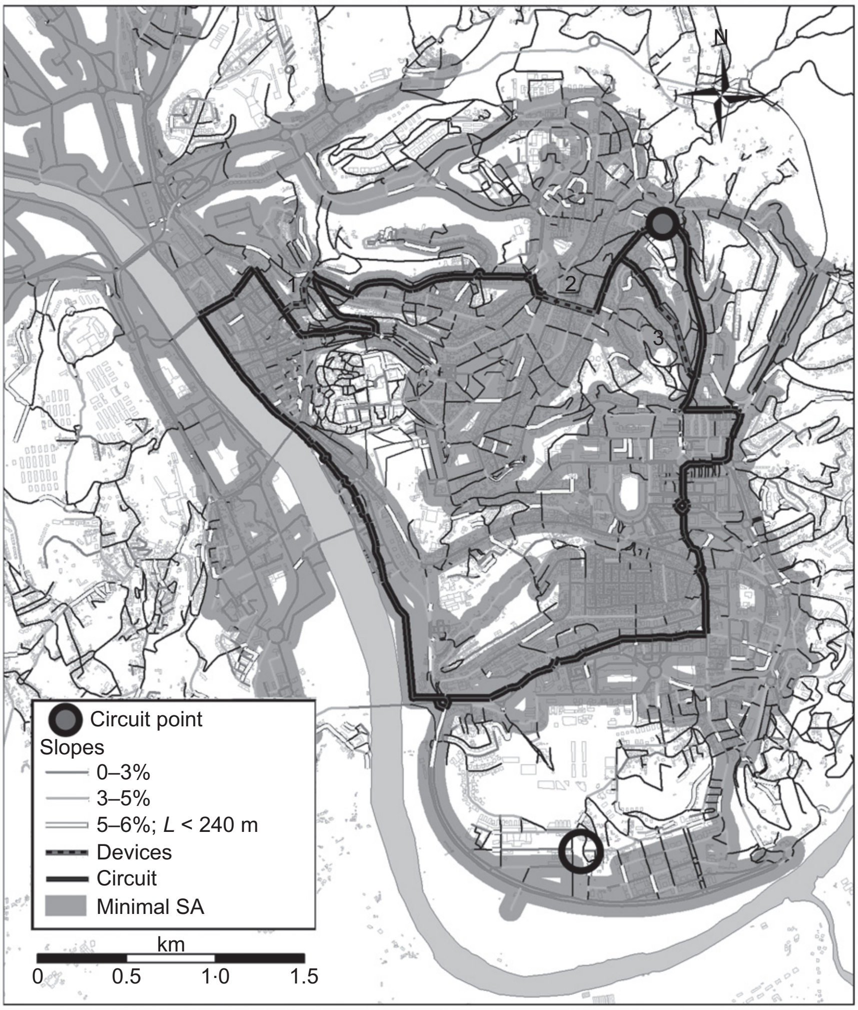

Figure 5. Bicycling circuit and final permeability zone

the main objective of which is to present the methodologies above. Note that it is convenient to endow the circuit with bicycle-friendly attributes, namely adequate lanes, traffic lights, priority rules, good track quality and low crossings density (e.g. Aashto, 2012; Austroads, 2009; Broach *et al.*, 2012; Crow, 2007; Wang *et al.*, 2008), which will lead to restrictions on the remaining traffic in some of its accesses. Such restrictions are usually not a problem because of the existence of alternative paths.

A population study reveals that about 51 000 inhabitants would benefit from the circuit. Along with connecting the 37 000 inhabitants of Z1, Z3 and Z4, the circuit provides permeability to an extra 14 000 inhabitants.

Besides the Old University hill (zone Z2), which will be discussed in Section 6, there is another zone not covered by the SA, located at the south of the study area. Making this zone permeable would require at least one aid device, to be located through the methodology described above (a tunnel is also possible). This zone is relatively uninhabited, but it contains, in its south-western tip, a part of the university campus II, which is only partially permeable. Still, since non-cyclable arcs on that tip are neither very long nor very steep (7–8% slopes), its most frequent users will certainly overcome the difficulties, because of their youth. Another option consists in placing a bicycle parking lot in its permeable part, as the walking paths to the campus are short. It is also possible to construct a small street (of approximately 50 m, circled in Figure 5 bottom), which would allow access to the campus.

6. Connecting the uptown university campus zone

As seen in Figure 3, a plateau point located in the uptown university campus generates a small service area, Z2, disconnected from the rest of the city. After introducing devices, this zone still remains disconnected. In fact there is a col in the path between the top-most point and Z2. Because this zone sits outside the cycling circuit of Section 5, it is interesting to study its connection without considering more devices.

One possibility to reach Z2 would be to use an already existing elevator, next to the marketplace (this is the one shown in Figure 4(b)). This elevator is in the permeable zone. The rest of the Z2 has descending paths of $s_{\text{down}} \leq 11\%$ and is thus cyclable downwards. Inbound cyclists coming from uptown may use the marketplace elevator, but it is possible to avoid it and access Z2 through a path of approximately 7·5% slope, 220 m sitting south-east of Z2 (this ramp sits at the end of the col). Although this path sits outside the Aashto table, it may eventually be considered a connection because the campus is used mainly by young people, and bike gears may permit it. Cyclists leaving Z2 heading uptown must go through two arcs: 6%/158 m and 6·8%/116 m. These sit inside the Aashto table and do not form a chain; they are thus cyclable both ways. Nevertheless, it may be advisable to place bicycle parking lots next to the marketplace elevator and at the beginning of the 7·5%/220 m path, and consider that cyclists reach the campus walking. The considerations of this section would make Z2 a trampoline from downtown (Z1) to uptown (Z3, Z4), but it does not seem like an adequate alternative to device 1, which links Z1 to Z3.

It is essential that arcs corresponding to the elevators also allow for pedestrian use, be it by using the sidewalk or the elevator itself. For example, device 3 is an excellent shortcut from the southeast part of the study area to its north section, where the university hospital sits (north part of Z3), along with some other important health services complexes.

7. Summary and outlook

In this research a methodology has been presented in order to study the suitability of a hilly city to cycling and make it more permeable to cycling. Based on the use of GIS, this methodology is generic and may be applied to any city, helping decision makers to plan their city for cycling. The suitability analysis and identification of improvements are important elements in any a priori cyclability study.

As future research, bike traffic generators and attractors could be defined and travel times between them evaluated; it would be interesting to compare with and without devices and/or circuit. The methodology can also be adapted to a number of other situations, such as the case of electrical power-assisted cycles (EPACs); in this case, devices would probably be unnecessary, making it interesting to compare scenarios, with respect to economic and energy costs. Another possibility would be to study cities whose street networks contain a lot of badly paved arcs (regardless of relief issues). It also would be a simple matter to configure GIS so as to model those arcs by means of sequences of artificial slopes and generate service areas accordingly. The emerging picture would then show which arcs should be given intervention priority, so as to provide connectivity.

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