

Design of bicycling suitability maps for hilly cities

Lino Tralhao, PhD

Researcher at INESC-Coimbra

Av. Antero Quental 199, 3000-141 Coimbra, Portugal

E-mail: linotralhao@netcabo.pt

Nuno Sousa, MSc, PhD

Invited Assistant Professor at Universidade Aberta, Researcher at INESC-Coimbra

Delegação de Coimbra da Universidade Aberta

R. Alexandre Herculano 52, 3000-019 Coimbra

E-mail: nsousa@uab.pt

Nuno Ribeiro, MSc

MSc in Civil Engineering INESC-Coimbra

Av. Antero Quental 199, 3000-141 Coimbra, Portugal

E-mail: nuno_r_@hotmail.com

João Coutinho-Rodrigues, MSc, PhD

Full Professor of Civil Engineering, Researcher at INESC-Coimbra

Department of Civil Engineering, Faculty of Sciences and Technology, University of Coimbra

Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

E-mail: coutinho@dec.uc.pt

Design of bicycling suitability maps for hilly cities

ABSTRACT

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 for urban sustainability given the associated environmental, economic and social advantages. Cycling however also has its deterrents. Among these, it is recognized that slopes play an important role in influencing the choice for this mode. The purpose of this paper is to present methods to analyse a hilly city's suitability for cycling, in what concerns relief, and with an aim at identifying locations for implementation of hard aid devices that restore connectivity between most, 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 planning the city in a sustainable way.

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 became 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, 2011). The bicycle is a means of transport that can be adopted in most cities, which combines the use readiness of the automobile, high efficiency, low congestion (one bicycle being roughly equal to 0.23 cars on road sections (Wang *et al.*, 2008)), health benefits (Woodcock *et al.*, 2007; Meschika, 2012) and quickness of travel for short distances (it is competitive with the automobile up to 5 km (Dekoster and Schollaert, 1999)).

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

One of these deterrents is relief, which it is known to have a strong negative impact on the propensity to use the bicycle on daily trips (Rietveld and Daniel, 2004; Parkin *et al.*, 2008). 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 upon hills for military reasons. It is the purpose of this research to present a methodology that will enable decision makers to evaluate the

1 topographic suitability of a city to cycling and to identify possible improvements to it. Albeit the issue
2 is recognized as an important one, the literature on it is, to best of our knowledge, scarce. This
3
4 research proposes to cover some of this ground by proposing a systematic way to take the relief effect
5
6 into account. The results generated by the methodology can then be plugged into existing models for
7
8 bicycle path or circuit planning purposes.
9

10 The methodology herein presented comprises four stages: classification of the city's streets
11 network with respect to slope and length, cyclability analysis, cycling permeability analysis and
12 identification of possible locations for mechanical aid devices. In the classification stage a
13 Geographical Information System (GIS) of the city is used to discriminate arcs of the streets network
14 according to slopes. This will form the basis for the subsequent analysis and is done in section 2,
15 together with the cyclability analysis, in the context of a case study, the hilly city of Coimbra,
16 Portugal. Coimbra is an old, mid-sized city, with a population of about 150 000 inhabitants, of which
17 circa 37 000 are students (see Figure 1, illustrative of one of the city's hills).
18
19
20
21
22
23
24
25
26
27
28
29
30

31 (Insert Figure 1 about here)
32
33
34
35

36 In the permeability analysis, appropriate service areas for bicycle use are obtained in GIS.
37 Having these areas makes it possible to identify disconnections in the network due to relief and how
38 to overcome them. This is done in section 3. Section 4 discusses the location of hard aid devices,
39 whose use would contribute to overcome disconnections in the cycling network, thus improving the
40 city's overall cyclability. In section 5 results for Coimbra are rounded up and a cycling circuit is
41 presented, which exemplifies how the outcome of proposed methodology can be useful as a basis for
42 broader studies. In section 6 a peculiar situation of the case study is highlighted, and shown as an
43 example of how to fine-tune the methodologies to deal with specific, casuistic aspects of a particular
44 city. Finally, section 7 conclusions and prospects are presented. This research makes use of ESRI
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

ArcGIS Desktop and its extension, the *Network Analyst*.

1
2 It should be noted that the illustrative case study dealt mainly with the core of the city of
3 Coimbra (designated as ‘study area’ below), with a particular emphasis on the part of the city
4 eastwards of the Mondego river, which is where most of the population lives and works.
5
6
7

8 **2. Network GIS modelling**

9

10 As mentioned, relief is an important issue when riding a bicycle, thus conditioning its massive use as
11 a transportation mode. Slopes (or grades) greater than 5% are undesirable because climbing the
12 ascents is difficult for many cyclists (AASHTO, 1999; AASHTO, 2012), while steep descents hamper
13 cyclists’ speed control. As an example of climbing difficulty, consider a path of 7% slope. Such an
14 incline is, on average, done at a speed of 3,21 m/s and power output at the pedal of 261W. These
15 values are presented in Parkin and Rotheram (2010), based on statistical (regression) work, and on the
16 well-known (Physics) formula:
17
18
19
20
21
22
23
24

$$25 \quad W = \frac{1}{\eta_m} (P_r + P_d + P_a + P_g) \quad (1)$$

26
27
28

29 Where W is the power at the pedal (human effort), η_m is the bicycle mechanical efficiency, $P_r + P_d$
30 the power dissipated given respectively the rolling resistance and the aerodynamic drag, P_a related to
31 acceleration (e.g. for kinetic energy reposition after a stop), and P_g , the most important component in
32 this work, the power related to gravitational energy:
33
34
35
36
37

$$38 \quad P_g = Mgv_s \quad (2)$$

39
40

41 where M is the man-machine mass, g the gravity acceleration, v the bike velocity (more precisely, the
42 horizontal component of it) and s the gradient (slope). Considering $M = 95$ kg, at 7% slope the
43 associated climbing power is $P_g = 209$ W, which accounts for a staggering 84% of the power at the
44 pedal, according to (1).
45
46
47
48
49

50 Regardless of figures, in practice human perception of the effort is also important. Because of
51 this, both Austroads and the American Association of State Highway and Transportation Officials
52 (AASHTO) have proposed desirable slopes of paths for ease of cycling (AASHTO, 1999; AASHTO,
53 2012; Austroads, 2009). The AASHTO gives the following guidance on slopes of paths and
54 respective acceptable lengths:
55
56
57
58
59
60
61
62
63
64
65

(Insert Table 1 about here)

1
2
3
4
5 The first task is therefore to classify the network arcs, with respect to slope and length. In the
6
7 *ArcGIS* environment, a streets network is modelled as follows: the arc between any two nodes
8
9 (crossings), A and B, is modelled as a polyline (piecewise linear curve). Only the sequence of vertex
10
11 coordinates (three coordinates for each vertex in 3D) of the polyline is stored. The first vertex of the
12
13 sequence is called “*From*”, and the last vertex “*To*”. Thus, for each arc, two directions exist: “*From-*
14
15 *To*” (the “reference” direction) and “*To-From*”, which means that the network is in fact a directed
16
17 network. Despite most streets having approximately constant slopes throughout their length, in some
18
19 cases that is not so. As such, and in our methodology, each arc is decomposed, with respect to its
20
21 reference direction, into three types of segments: ascending, descending and flat segments. Since
22
23 slope is constant in each of the segments, it is easily seen that, given (2), segments of each type can be
24
25 aggregated in only one combined part, having as length the sum of the lengths of its components, and
26
27 as slope the average of the slopes of their segments, weighted by their horizontal projections lengths.
28
29 Thus, each arc can be characterised by (l_{up}, s_{up}) , (l_{down}, s_{down}) and l_0 (flat length), where l_{up}
30
31 (l_{down}) are the sums of the ascending (descending) segments lengths, and s_{up} (s_{down}) the averages of
32
33 ascending (descending) slopes, weighted by their respective horizontal projection lengths. The arc
34
35 length corresponds to $l_{up} + l_{down} + l_0$. Note that everything that is *up* in the “*From-To*” direction
36
37 becomes *down* in the “*To-From*” direction and vice-versa. All these quantities were evaluated using
38
39 an auxiliary (Python) script implemented for this purpose and stored in associated tables. (In GIS
40
41 objects characteristics/attributes are stored in tables; usually sets of objects with the same geometry
42
43 and attributes have an associated table.)
44
45
46
47
48

49
50 An arc for which $s_{up}, s_{down} \leq 5\%$ is defined as *strictly cyclable*, i.e. cyclable in both
51
52 directions regardless of length. It is *weakly cyclable* if it has a slope (up or down) higher than 5% but
53
54 is nevertheless cyclable according to the AASHTO table in at least one direction. If both the ascents
55
56 and descents of a path are short enough, or if the path has a wavy profile, such a path would be easier
57
58 for the cyclist to ride (even if overall the path is an ascent) due to the speed gained from downslopes.
59
60
61
62
63
64
65

1 This issue may become important in borderline cases, particularly in slopes around 6%, which could
2 warrant these some sort of supplementary treatment. However the vast majority of the paths does not
3 have such a profile, which is why the arc characterisation mentioned above seems like a reasonable
4 enough approximation.
5
6
7

8 In Figure 2 a map of the network is presented. The arc greyscale tone corresponds to a GIS
9 generated colour code and depends on $\max\{s_{up}, s_{down}\}$. This is usually the value implied when an arc
10 is referred to as having x% slope.
11
12
13
14
15
16
17

18 (Insert Figure 2 about here)
19
20
21

22 From the figure, some strictly cyclable zones can be readily identified. These are
23 characterized by dominance of 0-5% arcs over large areas. Other parts of the city have weakly
24 cyclable arcs, but it is not easily seen whether those arcs can link important zones. An inspection
25 reveals that approximately 53% of the network (% of length) is cyclable. This includes isolated arcs,
26 but leaves aside weakly cyclable ones (12% of the network). The remaining arcs make up 35% of the
27 network and are non-cyclable, in the sense that they cannot be totally traversed in at least one
28 direction (according to the AASHTO table).
29
30
31
32
33
34
35
36

37 A note must be made here: adjacent arcs of 5-11% slope that are nevertheless cyclable may
38 raise a chain problem. That is to say, while each of them may be cyclable *per se*, if two or more lay in
39 succession, l_{up} of the path composed by those adjacent arcs may exceed AASHTO cyclability
40 bounds. This issue is addressed below where it was found to be relevant.
41
42
43
44
45
46
47
48

49 **3. Network permeability**

50

51 A given network zone is considered *permeable to cycling* if it allows the travelling by bicycle
52 between any two of its points, back and forth. In the context of this research, the concept revolves
53 around allowing the cyclist long trips (e.g. commuting), covering a great part (or even the whole) of
54 the study area. In the case of a hilly city, it is likely that aid devices will prove necessary. Thus
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

cyclability, as defined in section 2, is not 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 minimize 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, cyclable in both directions. In this way, to move between any two locations in the city, a cyclist could (1) ride towards the circuit, (2) traverse part of it, (3) exit it towards its 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 topmost and bottommost 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 topmost spot. Also, as the bottommost spot is accessible from all the others (with the aforementioned exceptions) and connects, via circuit, the topmost, a significant part of the study area points gets connected as well. This is what happens 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 above paragraphs are taken into account in the methodology proposed here for finding the permeable zones. Before addressing it, it is convenient to briefly explain 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 programed/parameterized for this purpose. In short, the NA allows the analysis of specific network configurations/parameterizations, and can perform several types of studies over it, such as routing, i.e. finding least impedance paths, and the determination of service areas (SA), this one in fact 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

1 for the configuration/parameterization at hand. Facility points are the roots of these trees. The SA is
2 the area obtained connecting those “ends” by line segments, generating polygons. These polygons
3 engulf areas in-between tree arcs, but there is an option, always used in this research, to snip the
4 polygons (*Trim Polygon*), so as to remove from them parts more than a certain distance away from the
5 tree arcs. The resulting SA is thus an area made out of points up to a certain distance from the tree
6 arcs (an area up to a certain distance from an object is called a *buffer*). Tree branches may eventually
7 end before finding a restricted arc because a maximum impedance may be assigned for paths (*Default*
8 *Break*). All the above refers to *away* service areas (i.e. “where can you go, starting from facility”), but
9 it also applies to *toward* service areas, i.e. SA determined in the opposite direction, towards the
10 facility.

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

17 In the second step, the network is configured/parameterized (in the context of the *Network*
18 *Analyst*) s.t. all arcs not strictly cyclable are restricted. Arcs not suitable for cycling (some bridges and
19 speedways) were also restricted.

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

26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58 (Insert Figure 3 about here)
59
60
61
62
63
64
65

1 Alongside with service areas, Figure 3 also displays borderline arcs with $5\% < (s_{up}, s_{down}) \leq 6\%$
 2 and $(l_{up}, l_{down}) \leq 240$ m, in white. Because of their relevance for connection of zones, some of
 3 these arcs are potential candidates for infrastructural improvements. That is the case of the four
 4 leftmost paths circled in black in Figure 3. These paths are important for connecting several zones and
 5 do not form chains. From inspection of the service areas and 5-6% paths, it can be seen that a
 6 significant portion of the southern part of city and riverside can be made permeable (zone Z1,
 7 ‘downtown’). Note that it is irrelevant whether the SA is *away* or *towards* because non-restricted arcs
 8 are strictly cyclable.
 9

10 Since the topmost and bottommost spots are in the obtained SA, it is clear that, aside from the
 11 aforementioned col zones and excessive slopes, if it were somehow possible to “fill-in” the existent
 12 disconnections, the whole, or at least a great deal, of the study area will become permeable. Thus, and
 13 in the last step of the permeability study, a detailed analysis of the arcs sitting at disconnections of the
 14 SA was made.
 15

16 Finding directed paths connecting two sub-SA can be done in a systematic way as follows.
 17 Since all arcs in a sub-SA are strictly cyclable, use the *Network Analyst* routing option and consider
 18 two points, X and Y, each one in a sub-SA. Forbid all arcs with (s_{up}, l_{up}) outside the AASHTO table
 19 and those with $s_{down} > 11\%$. Then consider classes of slopes, e.g. 0-5%, 5-6%, 6-8%, 8-11% (up),
 20 $\leq 11\%$ (down), 0%, and find the shortest routes from X to Y, and from Y to X, using the impedance
 21 function
 22

$$23 \quad w_1 \sum_j l_j^{(1)} + w_2 \sum_j l_j^{(2)} + \dots + w_N \sum_j l_j^{(N)}$$

24 where N is the number of classes, w_i the weight for route components of class i and $\sum_j l_j^{(i)}$ the length
 25 of class i components of the route (may be zero). The set of weights works as a filter because relative
 26 lower weights increase the preference for components of their classes. This property may be used to
 27 find 0-6% connections or to try to avoid the chain problem (higher weights help in that respect). If
 28 this procedure finds two paths, one for each direction, between two sub-SA, a connection between
 29 those sub-SA is then established. Eventually all of the zone sitting between them also gets connected,
 30 except if there are hills, cols or excessive downhill slopes in that zone (which is not the case in
 31
 32
 33
 34
 35
 36
 37
 38
 39
 40
 41
 42
 43
 44
 45
 46
 47
 48
 49
 50
 51
 52
 53
 54
 55
 56
 57
 58
 59
 60
 61
 62
 63
 64
 65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

general). This procedure can be generalized considering several points in each sub-SA, located where these sub-SA 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 – c.f. 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 via a west-side two-way connection next to the river and also, (in the north-south direction only), via a path in its east side (rightmost black circle in Figure 3). The later allowed to include in the permeable zone 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 looked upon in more detail in another section. Of these devices, only device 3 cannot be done without, since it climbs to the study zone's topmost 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 e.g., elevators, funiculars, stairways/ramps, or tunnels, even though the later are not the focus of this work. Figure 4 illustrates two types of aid devices (right: elevator, left: cyclocable – see it in action at <https://www.youtube.com/watch?v=JtB8DX70ihM>).

(Insert Figure 4 about here)

1 In choosing device locations, priority should be given to overcoming as high a slope as possible (this
2 usually implies short lengths). One way to achieve this consists in trying to use already existing arcs,
3 using the routing option of the NA and a technique similar to the one of section 3 for finding
4 connecting paths; the impedance function consisting now of a convex combination of $1/s_{up}$ and
5
6 $L = l_{up} + l_{down} + l_0$ (for s_{up} values close to zero, artificial values can be assigned to $1/s_{up}$).
7
8 Another way, which is necessary when the connecting arcs are non-existent, is to choose a new path,
9 independent of the existing network. Like the previous approach, choosing this path is casuistic in
10 nature. The first strategy was followed for obtaining the locations for devices 2 and 3, whereas the
11 second one was used for device 1. Naturally, other criteria could be considered, eventually leading to
12 different locations for the devices. Also, more devices (other than just the three presented) could also
13 be considered, so as to reduce distances even further.
14
15
16
17
18
19
20
21
22
23
24
25
26

27 **5. A possible main bicycling circuit**

28 Another motive for preferring three devices in the case study is that their alignment clearly suggests
29 the ring-like, fully cyclable, bicycle circuit of Pucher (1997). The devices would make up part of its
30 north section. A possible circuit is presented in Figure 5.
31
32
33
34
35
36
37

38 (Insert Figure 5 about here)
39
40
41

42 This circuit's main characteristic is that it can be cycled in both directions. Thus, the SA
43 corresponding to the circuit is the SA of any point of the circuit (the SA could also be obtained from
44 the circuit itself). Furthermore, the SA corresponding to the circuit will correspond to the permeable
45 zone of the area under study. Unfortunately, the chain problem makes it difficult to obtain that SA
46 exactly. It is however possible to obtain a "minimal permeability zone" by opening directed arcs with
47 $s_{up} \leq 5\%$ e $s_{down} \leq 11\%$ (besides the ones in the circuit, as well as those connecting sub-SA). The
48 resulting SA, obtained from the circuit point circled in black is presented in Figure 5 (top). Enabling
49 all directed arcs with (l_{up}, s_{up}) respecting the AASHTO table and $s_{down} \leq 11\%$ a "maximal
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 permeability zone” is obtained, which, interestingly, does not differ significantly from the minimal
2 area (hence not presented).
3

4 At the network level, the aid device has a travel time, t , associated to it. Thus, to model
5 devices as network arcs (in a way that is consistent with other arcs – see section 2), flat arcs with
6 equivalent length $l_0 = vt$ were used. Any positive cycling speed v can be assigned (6 m/s was used).
7
8

9 For device 2 the streets are wide enough to accommodate a descending lane; for the two other
10 devices the descending paths are separate, but also part of the circuit.
11
12

13 The circuit includes two already existing bikepaths (though in need of improvements). There
14 are not many alternatives paths for the circuit in the north, south and east sectors of it. This is not the
15 case for its west sector (mainly northwest), which crosses the centre of the city and warrants a more
16 thorough study. This is however outside the focus of this paper, whose main objective is to present the
17 methodologies above. Note that it is convenient to endow the circuit with bicycle-friendly attributes,
18 namely adequate lanes, traffic lights, priority rules, good track quality and low crossings density (e.g.
19 AASHTO, 2012; CROW, 2007; Wang *et al.*, 2008; Austroads, 2009; Broach *et al.*, 2012), which
20 will lead to restrictions on the remaining traffic in some of its accesses. Such restrictions are usually
21 not a problem because of the existence of alternative paths.
22
23
24
25
26
27
28
29
30
31
32
33
34
35

36 A population study reveals that about 51 000 inhabitants would benefit from the circuit.
37 Along with connecting the 37 000 inhabitants of Z1, Z3 and Z4, the circuit provides permeability to
38 an extra 14 000 inhabitants.
39
40
41

42 Besides the Old University hill (zone Z2), which will be treated in section 6, there is another
43 zone not covered by the SA, located at the south of the study area. Making this zone permeable would
44 require at least one aid device, to be located through the methodology described above (a tunnel is
45 also possible). This zone is relatively uninhabited, but it contains, in its south-western tip, a part of the
46 University Campus II, which is only partially permeable. Still, since non-cyclable arcs on that tip are
47 neither very long nor very steep (7-8% slopes), its most frequent users will certainly overcome the
48 difficulties due to their youth. Another option consists on placing a bicycle parking lot in its
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1 permeable part, as the walking paths to the campus are short. It is also possible to construct a small
2 street (of approximately 50 m, circled in Figure 5 bottom), which would allow access to the campus.
3
4
5

6. Connecting the uptown university campus zone

6
7
8 As seen in Figure 3, a plateau point located in the uptown university campus generates a small service
9 area, Z2, disconnected from the rest of the city. After introducing devices, this zone still remains
10 disconnected. In fact there is a col in the path between the topmost point and Z2. Because this zone
11 sits outside the cycling circuit of section 5, it is interesting to study its connection without considering
12 more devices.
13
14
15
16
17
18

19 One possibility to reach Z2 would be to use an already existing elevator, next to the
20 marketplace (this is the one shown in Figure 4 – right). This elevator is in the permeable zone. The
21 rest of the Z2 has descending paths of $s_{down} \leq 11\%$ and is thus cyclable downwards. Inbound
22 cyclists coming from uptown may use the marketplace elevator, but it is possible to avoid it and
23 access Z2 through a path of approximately 7.5% slope, 220 m sitting southeast of Z2 (this ramp sits at
24 the end of the col). Although this path sits outside the AASHTO table, it may eventually be
25 considered a connection because the campus is used mainly by young people, and bike gears may
26 permit it. Cyclists leaving Z2 heading uptown must go through two arcs: 6%/158 m and 6.8%/116 m.
27 These sit inside the AASHTO table and do not form a chain; they are thus cyclable both ways.
28 Nevertheless, it may be advisable to place bicycle parking lots next to the marketplace elevator and at
29 the beginning of the 7.5%/220 m path, and consider that cyclists reach the campus walking. The
30 considerations of this section would make Z2 a trampoline from downtown (Z1) to uptown (Z3, Z4),
31 but it doesn't seem like an adequate alternative to device 1, which links Z1-Z3.
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

48 It is essential that arcs corresponding to the elevators also allow for pedestrian use, be it via
49 the sidewalk or the elevator itself. For example, device 3, is an excellent shortcut from the southeast
50 part of the study area to its north section, where the University Hospital sits (north part of Z3), along
51 with some other important health services complexes.
52
53
54
55
56
57
58
59
60
61
62
63
64
65

7. Summary and outlook

In this research a methodology was 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 (EPAC cycles); 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 streets network contains 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.

Acknowledgements

A tribute must be paid to FCT (the Portuguese Foundation for Science and Technology), who partially supported this research work under project grant PEst-OE/EEI/UI308/2014, and project *Energy and Mobility for Sustainable Regions* (EMSURE) – ref. CENTRO-07-0224-FEDER-002004, framed under the initiative *Energy for Sustainability* of the University of Coimbra.

References

- AASHTO (1999). *AASHTO Guide for the Development of Bicycle Facilities*. American Association of State Highway and Transportation Officials – AASHTO (ed.), USA. ISBN: 1560511028.
- AASHTO (2012), *AASHTO Guide for the Development of Bicycle Facilities*. American Association of State Highway and Transportation Officials – AASHTO (ed.), USA. ISBN: 1560515272.
- Austroroads (2009) *The Guide to Road Design – Part 6A: Pedestrian and Cyclist Paths*. Austroroads Publications (ed.), Publication no. AGRD06A-09. ISBN: 9781921551819

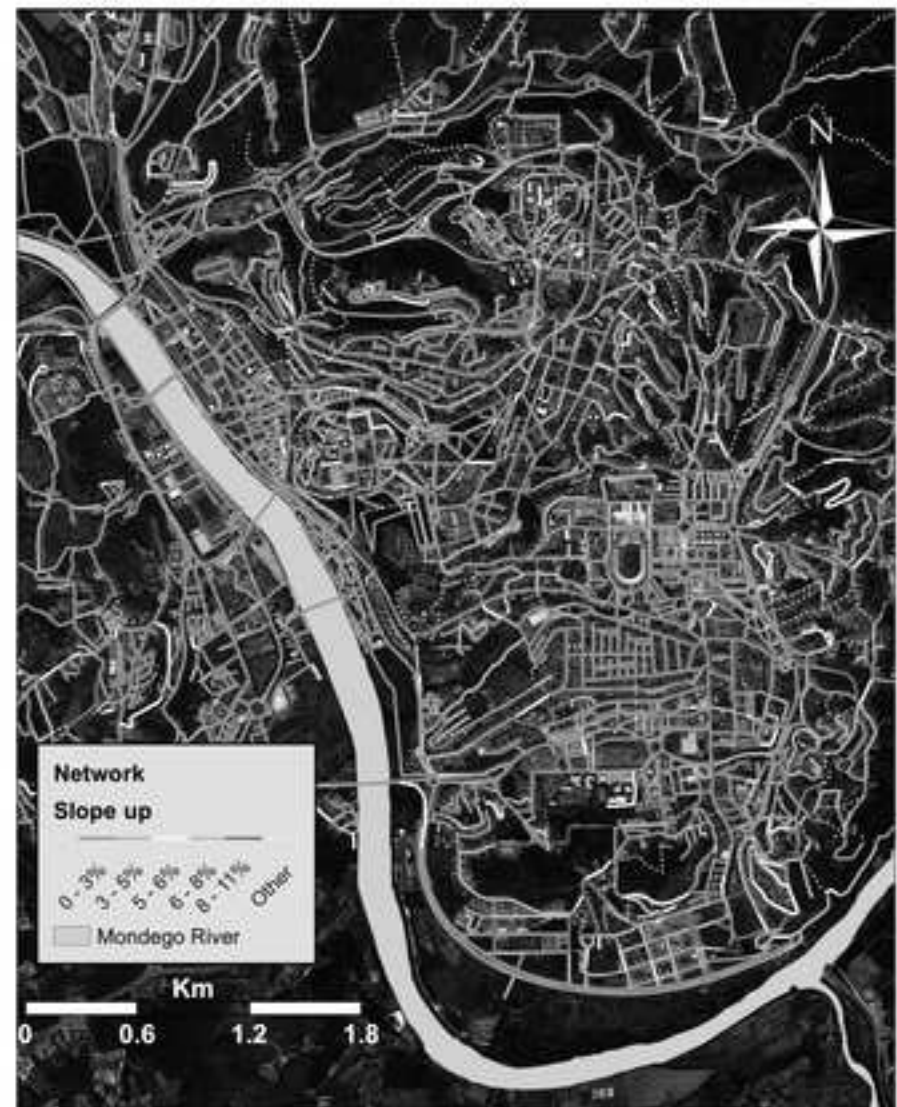
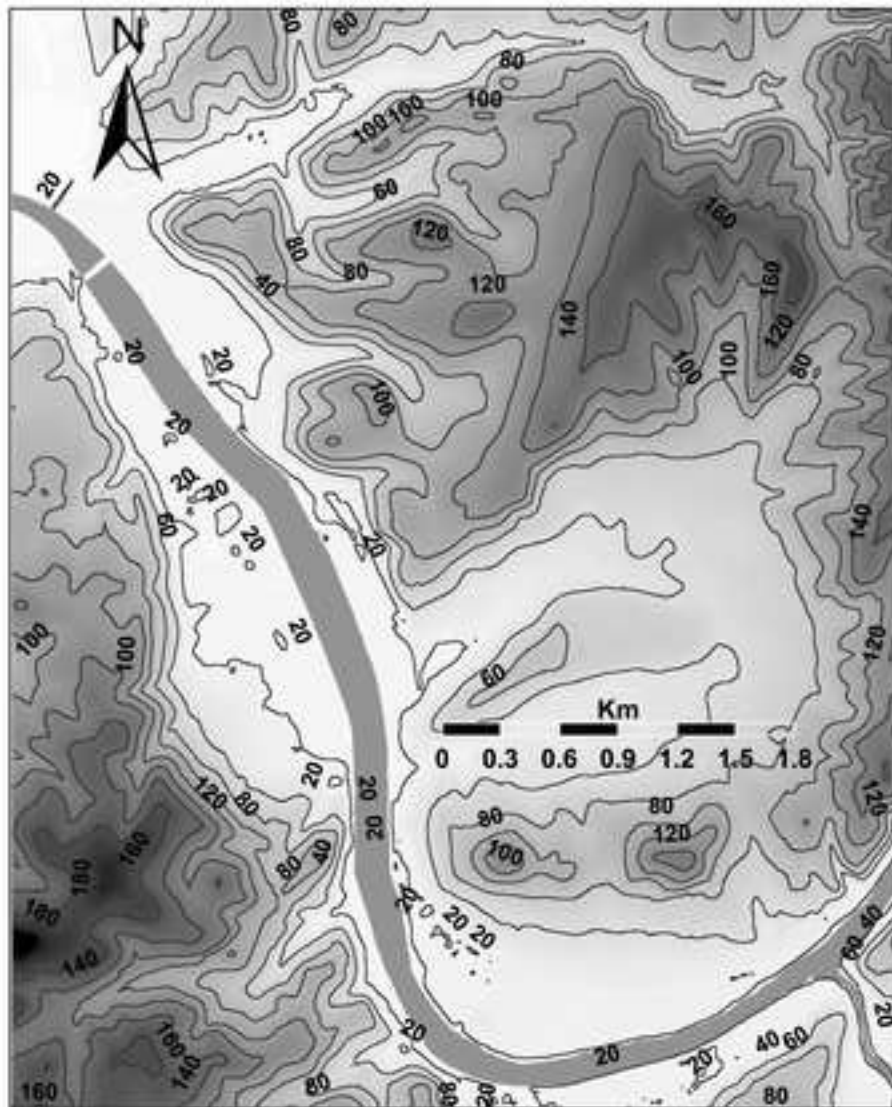
- 1 Broach J, Dill J and Gliebe J (2012) Where do cyclists ride? A route choice model developed with
2 revealed preference GPS data. *Transportation Research Part A* **46**:1730–1740.
3 <http://dx.doi.org/10.1016/j.tra.2012.07.005>
- 4 BYPAD (2008). *Cycling, the European Approach – Total quality management in cycling policy,*
5 *Results and lessons of the BYPAD-project*. Bicycle Policy Audit, European Commission
6 project. Link: http://bypad.org/docs/BYPAD_Cycling_The_European_approach.pdf
7
- 8 Cervero R, Caldwell B and Cuellar J (2012) Bike-and-Ride: Build It and They Will Come. (Working
9 paper.) Institute of Transportation Studies, University of California (ed.), Berkley, USA.
10 <http://its.berkeley.edu/publications/UCB/2012/VWP/UCB-ITS-VWP-2012-5.pdf>
11
- 12 CROW (2007). *Design manual for bicycle traffic*. CROW (ed.), The Netherlands. ISBN:
13 9789066284944.
14
- 15 Dekoster J, and Schollaert U (1999) *Cycling: the way ahead for towns and cities*. Office for Official
16 Publications of the European Communities, Luxembourg. ISBN 92-828-5724-7.
17
- 18 Kenworthy J (2011) *Energy Use and CO2 Production in the Urban Passenger Transport Systems*
19 *of 84 International Cities: Findings and Policy Implications*, in Droege, Peter (ed.) - *Urban*
20 *Energy Transition* (Chapter 9), Elsevier. ISBN 9780080453415
21
- 22 Lefèvre B (2009) Urban Transport Energy Consumption: Determinants and Strategies for its
23 Reduction. An analysis of the literature, *S.A.P.I.EN.S* **2(3)** Cities and Climate Change.
24 <http://sapiens.revues.org/914>
25
- 26 Meschika M (2012) Reshaping city traffic towards sustainability - Why transport policy should favor
27 the bicycle instead of car traffic. *Procedia - Social and Behavioral Sciences* **48**:495-504.
28 <http://dx.doi.org/10.1016/j.sbspro.2012.06.1028>
29
- 30 Parkin J and Koorey G (2012) Network planning and infrastructure design. In: Parkin J. (ed). *Cycling*
31 *and Sustainability*. (1) 1st. Bingley: Emerald Books, pp.131-160. ISBN 9781780522982
32
- 33 Parkin J and Rotherham J (2010) Design speeds and acceleration characteristics of bicycle traffic for
34 use in planning, design and appraisal. *Transport Policy* **17**:335-341.
35 <http://dx.doi.org/10.1016/j.tranpol.2010.03.001>
36
- 37 Parkin J, Wardman M and Page M (2008) Estimation of the Determinants of Bicycle Mode Share for
38 the Journey to Work using Census Data. *Transportation* **35**:93-109. Link:
39 <http://EconPapers.repec.org/RePEc:kap:transp:v:35:y:2008:i:1:p:93-109>
40
- 41 Parkin J, Wardman M and Page M (2007) Models of perceived cycling risk and route acceptability.
42 *Accident Analysis and Prevention* **39**:364–371. <http://dx.doi.org/10.1016/j.aap.2006.08.007>
43
- 44 Pucher J, Buehler R and Seinen M (2011) Bicycling renaissance in North America? An update and re-
45 appraisal of cycling trends and policies. *Transportation Research Part A* **45**:451-475.
46 <http://dx.doi.org/10.1016/j.tra.2011.03.001>
47
- 48 Pucher J and Buehler R (2008) Making Cycling Irresistible: Lessons from The Netherlands, Denmark
49 and Germany. *Transport Reviews* **28(4)**:495-528.
50 <http://dx.doi.org/10.1080/01441640701806612>
51
- 52 Pucher J, Komanoff C and Schimek P (1999) Bicycling renaissance in North America?: Recent trends
53 and alternative policies to promote bicycling. *Transportation Research Part A* **33(7-8)**:625-654.
54 Link: [http://dx.doi.org/10.1016/S0965-8564\(99\)00010-5](http://dx.doi.org/10.1016/S0965-8564(99)00010-5)
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
- Pucher J (1997) Bicycling Boom in Germany: A Revival Engineered by Public Policy. *Transportation Quarterly* **51(4)**:31-46.
- Rietveld P and Daniel V (2004) Determinants of bicycle use: do municipal policies matter? *Transportation Research Part A* **38**:531-550. <http://dx.doi.org/10.1016/j.tra.2004.05.003>
- Suzuki K, Kanda Y, Doi K and Tsuchizaki N (2012) Proposal and Application of a New Method for Bicycle Network Planning. *Procedia - Social and Behavioral Sciences* **43**:558-570. <http://dx.doi.org/10.1016/j.sbspro.2012.04.129>
- Wardman M, Tight M and Page M (2007) Factors influencing the propensity to cycle to work, *Transportation Research Part A* **41(4)**:339-350. <http://dx.doi.org/10.1016/j.tra.2006.09.011>
- Wang D, Feng T and Liang C (2008) Research on bicycle conversion factors. *Transportation Research Part A* **42**:1129-1139. <http://dx.doi.org/10.1016/j.tra.2008.03.016>
- Woodcock J, Banister D, Edwards P, Prentice AM and Roberts I (2007) Energy and transport. *The Lancet* **370(9592)**:1078-1088. [http://dx.doi.org/10.1016/S0140-6736\(07\)61254-9](http://dx.doi.org/10.1016/S0140-6736(07)61254-9)

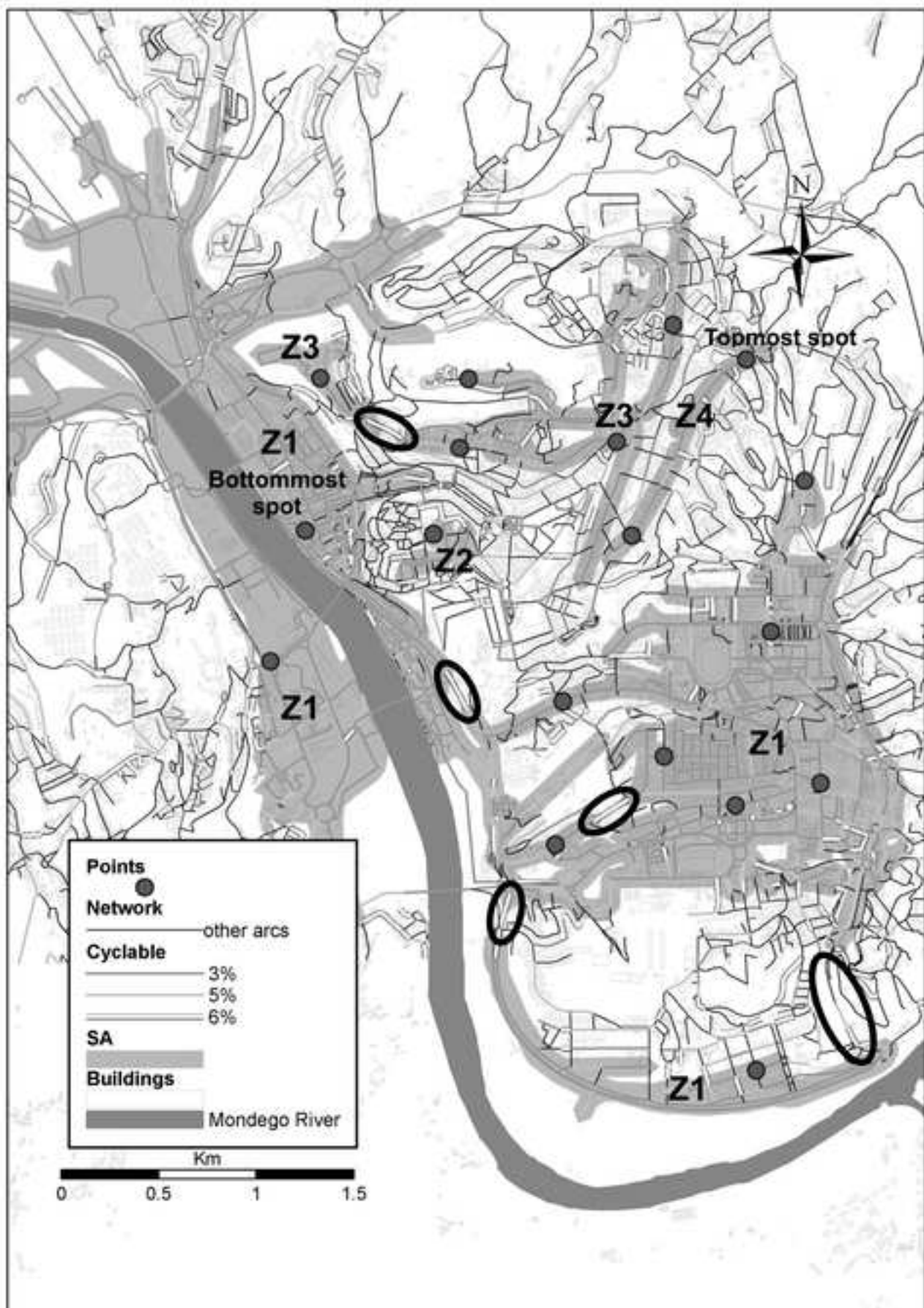
Figure_1
[Click here to download high resolution image](#)



Figure_2
[Click here to download high resolution image](#)



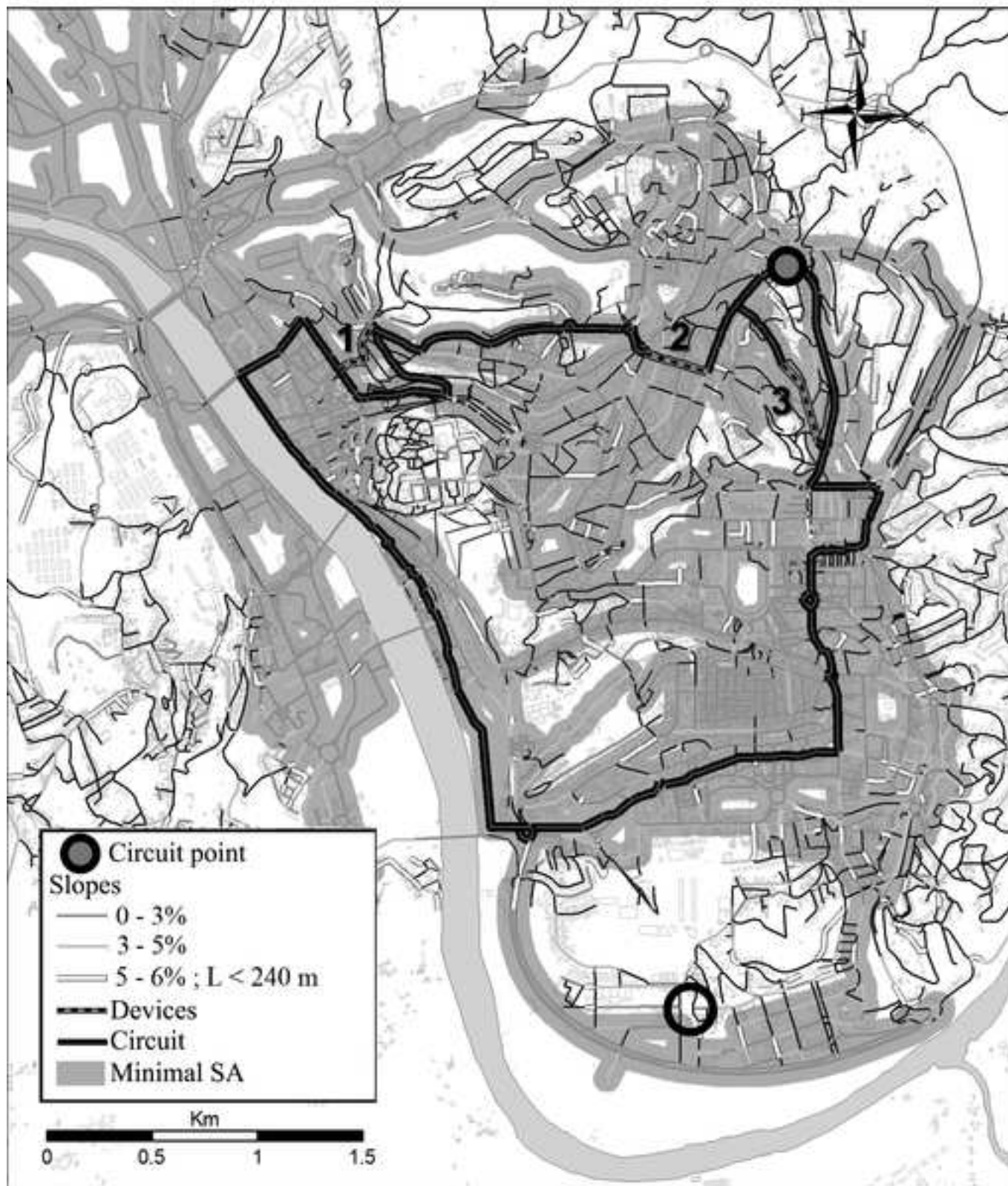
Figure_3
[Click here to download high resolution image](#)



Figure_4
[Click here to download high resolution image](#)



Figure_5
[Click here to download high resolution image](#)



Table_1

[Click here to download Table: Table_1.docx](#)

Slope	Acceptable Length
5-6%	240 m
7%	120 m
8%	90 m
9%	60 m
10%	30 m
11+%	15 m

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Figure 1. City of Coimbra – University hill.

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

Figure 3. Set of points SA – disconnections.

Figure 4. Hard aid devices – cyclocable (left), elevator (right).

Figure 5. Bicycling circuit and final permeability zone.

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