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Growing from incipient to potentially large cycle networks: screening the road network of the consolidated urban area of Lisbon

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Many arguments sustaining active modes of transport are related to ameliorating urban life. Biking should be one option for our daily trips including utilitarian trips and not only trips for leisure. Accordingly, designing cycle networks that meet citizens' requirements for daily trips is important to increase modal share. Particularly, it should take into account coherence, directness and attractiveness/comfort, not overlooking safety issues towards other road vehicles. Furthermore, it must consider also the current limitations of existing roads (lane width or gradient), in order not to hinder excessively existing road traffic while rearranging the carriageway for suitable cycle network.

These objectives become more challenging when aiming to enlarge an incipient cycle network and make it grow to a large and ubiquitous one, in hilly and consolidated urban areas. The present research proposes a practice-ready method to be implemented for screening the existing road network to potentially rearrange the existing carriageway and accommodate a cycling network in urban areas with such characteristics. The methodology suggests also key indicators to analyze the potential performance of the cycle network, at an early planning stage.

Although applied to Lisbon, the cycle network screening method is potentially relevant for countries where major urban agglomerations stand in hilly land and still want to see their cyclists grow in the next years. We conclude that it is possible to potentially fit a large cycle network of almost 20% of Lisbon's total road network. The possible network configurations obtained are assessed in terms of coherence, directness and attractiveness/comfort for bikers. Finally, construction costs of the cycle networks obtained were compared.

Keywords: *Active modes; cycling network; planning and design; performance assessment indicators; Lisbon.*

1. Introduction

Many arguments sustaining active modes of transport are related to ameliorating urban life. Biking should be one option for our daily trips including utilitarian and not only for leisure. Accordingly, designing cycle networks that meet citizens' requirements for daily trips is

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important to increase cycling modal share. Many cities have greatly improved their shares of cycling trips: Washington, DC, tripled in 18 years; six-fold increase in Portland, Oregon (Pucher & Buehler, 2012). Still these are far below Amsterdam (34%) and Copenhagen (37%) (Pucher & Buehler, 2008). As put by Handy et al (2014), the two significant challenges for many cities to increase the transport cycling is, firstly, to identify the more effective ways to spend the limited resources that have been allocated to cycling (many times bundled with pedestrian into active modes together) and, secondly, justifying the allocation of a greater share of limited transport resources to cycling. This makes it even harder when starting from an incipient cycle network under economical strain, such as in Lisbon today. Still, private car is by far the most used mode, even though its negative impacts and undesirable aspects regarding traffic congestion, safety and pollution. Cycling, in turn, is a clean and energy efficient mode and it is particularly well suited to many of the trips in central urban areas, in many cases performed by cars nowadays (Pucher & Buehler, 2008). Many utilitarian daily trips, such as travelling to work or to school, are shorter than 5km, where bikes can compete with cars in terms of travel time (European Commission, 1999). Also, cycling offers relevant environmental and health benefits for the community (UK Department for Transport, 2008), besides being more economical and contributing potentially to the reduction of road congestion. Therefore, it should be included in urban and transport planning standard practice irrespective of the scale of analysis, i.e. shorter trips in the city centres or longer commuter routes. Acknowledgement of cyclists in the urban mobility outreach ensures that current planning decisions meet future needs in terms of providing appropriate facilities that can avoid jeopardizing the important role this mode could and should play in the growing demographics of near future cities (Dufour, 2010).

The commitment in promoting bicycle use is currently of high priority in many countries (Austroads Ltd et al., 2014; Kokotailo, 2006; UK Department for Transport, 2008). Accordingly, designing cycle networks that meet citizens' requirements for daily trips is important to increase cycling modal share. Particularly, it should take into account criteria such as coherence, directness and attractiveness/comfort (refer to section 4.4 for the definition of these indicators), always ensuring safety requirements for bikers. Nevertheless, it must consider also the current limitations of existing roads, namely in terms of width or gradient, in order not to hinder excessively existing road traffic while rearranging it for a suitable cycle network. These objectives become more challenging when aiming to enlarge an incipient cycle network and make it grow to become large and ubiquitous, in hilly and consolidated urban fabrics, like the one in Lisbon.

This paper proposes a methodology for analysing the potential for rearranging the existing road network (carriageway) and accommodate a cycling network in consolidated urban areas while minimizing the reduction of road network capacity for motorized vehicles. It also presents some key indicators to analyse the performance of the cycle network, at an early planning stage. These indicators relate mostly to connectivity, redundancy and attractiveness of the cycle network.

After this introduction, Section 2 presents a brief review of the literature regarding cycle network planning. Section 3 presents the case of Lisbon with respect to cycling. Next, Section 4 presents overall methodology and methods used here, while section 5 describes the main results obtained and corresponding discussion. We end with some conclusions and recommendations for future research in section 6.

2. Planning cycling networks

Research on bicycle-related topics has increased significantly over last decade, specially since 2010. Studies have addressed cycling infrastructure aspects, cycling behaviour – such as profiling users (Dill and McNeil, 2013) or preferred route choices (Broach et al, 2012) –, public policies for bicycle use (for instance, Pucher et al, 2011), cycling and health (Pucher et al, 2010, Dill, 2009), not to mention all related topics.

One important aspect that is still being greatly reported is the importance of providing cycling facilities and infrastructures for the uptake of bicycle share in urban areas. Dill and Carr (2003) analysed how the infrastructure guides the existing and potential cyclist behaviour by studying cross-sectional samples from multiple cities. The main conclusion is that cities with higher levels of infrastructure (lanes and paths) witness higher levels of bicycle commuting. While some authors have confirmed that the presence of new cycling infrastructure drives the behaviour of cyclists (Hopkinson and Wardman, 1996; Krizek et al, 2007; Cervero et al. 2009; Larsen and El-Geneidy 2011, Broach et al, 2012), other have found that sometimes improving current road network might have bigger impacts on the cyclist number of trips (Aultman-Hall et al, 1997). On the other hand, Moudon et al (2005) tempers this view and has found that cycling is only moderately associated with the neighbourhood environment and individual choice is independent from environmental support (including bicycle infrastructures). Pucher et al (2011) highlight the case of nine cities in the US and Canada where not only cycling facilities were widely deployed (up to 73km/100 000 residents in Portland), but additional urban mobility policies complemented the uptake of bicycle share (that reached 6-fold increase in Portland over 2 decades), such as traffic calming, parking, bike-transit integration, bike sharing, training programs, and promotional events. Previously, Pucher et al (2010) showed that almost all 14 cities adopting comprehensive packages of interventions experienced large increases in the number of bicycle trips and share of people bicycling, where public policy in encouraging bicycling played a crucial role.

Many manuals have been made freely available by authorities, providing guidelines for planning, designing, building and maintaining cycle networks. For instance, the Austroads manual (2014) defines a bicycle network as an enabler of cyclists with a wide range of abilities and experience to move safely and conveniently to chosen destinations via suitable desire lines. Importantly, this manual also refers that the basis of a bicycle network is the road network, augmented by special on-road facilities together with dedicated infrastructure such as off-road paths, and footpaths where permitted, and may include public transport (i.e., bus & bike lanes). These manuals provide highly detailed information and statistics on how to design and operate the several components of a cycle network, from bicycle lanes (when a portion of a roadway is been designated by striping, signing and pavement markings for the exclusive use of bicyclists), bike paths (when a bikeway is physically separated from motorized vehicular traffic by an open space or any other physical barrier), bike boxes (green box on the road with a white bicycle symbol inside at signalized intersection), among other features. Besides the Australian manual, we can refer to a few others, starting by the seminal manual "Design manual for bicycle traffic" by CROW (2007), European Commission's PRESTO guide (PRESTO, 2010), NACTO's Urban bikeway design guide (2011, nacto.org/publication/urban-bikeway-design-guide/), Portland's "Bikeway facility design: survey of best practices" (https://www.portlandoregon.gov/transportation/), Chicago's Bike Lane Design Manual (www.bicyclinginfo.org), the "Cycle Infrastructure Design -Local Transport Note 2/08", by Department for Transport of the UK, "Rede Ciclável - Princípios de Planeamento e Desenho" of the Portuguese Transport and Mobility Authority (2011 – www.imtt.pt), the Irish National Cycle Manual (2011, www.cyclemanual.ie), among many others.

The foundational principles when planning for a bicycle network are found in most of these plans and can be summarized as follows:

- Link geographic locations with an adequate and functional network that privileges accessibility through a distributed organization throughout the city;
- Provide bicycle infrastructures that reduces delay or diversion and improves safety;

- The road network is the most basic (and important) cycling facility available, and the preferred way of providing for cyclists is to create conditions on the carriageway where cyclists are content to use it;
- Whenever possible, privilege sharing space with motorized vehicles over separated infrastructures; and
- Integration in with other modes, other transport plans and urban plans, at an early planning stage of the network.

Many of these manuals provide also insights on how to prepare a bike plan (for example, refer to the Australian guide on "How to prepare a bike plan", www.rms.nsw.gov.au). However, there is little research on how to choose and prioritize locations for cycling infrastructures. Larsen et al (2013) have proposed a GIS-based, grid-cell model for bicycle facility prioritization and location, which they have applied to Montreal, Canada. The approach is to define the potential of each cell to generate and attract bicycle trips, and where new cycling facilities would provide the maximum benefit to both existing and potential cyclists. The tool aims to support decision-making to prioritize and select different infrastructure investment scenarios for cycling networks. Other studies have used GIS to locate transport infrastructures. For instance, Horner and Grubesic (2001) used a GIS-based planning approach to locating urban rail terminals. Garcia-Palomares et al (2012) have also used a GIS approach for optimal location of bike-sharing stations in Madrid (Spain). As explained in more detail in section 4, many indicators have been proposed to analyse the performance of cycling networks regarding the connectivity, fragmentation and other important dimensions. Particularly, the CROW design manual (2007) has suggested that cycle networks should aim to a maximum mesh width of 200 to 250 meters although 400 meters was defined for the London Cycle network plan (SUSTRAN, 2014). This reference metric allows also to identify zones of an urban area that are less covered by the cycle network – i.e., 'black spots' where a significant part of that zone is more than 250 meters apart from any cycling infrastructure.

The work presented here is based on the GIS and cycling literature with the objective to contribute to fill the gap of bicycle network planning literature, by proposing a practice-ready method to be implemented for screening the existing road network to potentially rearrange the existing carriageway and growing from incipient to potentially large cycle network in hilly cities with consolidated urban areas. The methodology suggests also key indicators to analyse the potential performance of the cycle network, at an early planning stage. We apply this straightforward method to the case-study of Lisbon, that we described in the next section.

3. Cycling in Lisbon today

Lisbon has roughly 550 000 inhabitants, while Lisbon Metropolitan Area (LMA) has more than 2.4 million. Like in the majority of bigger cities, private car holds a large share of commuting trips (34%), while public transport modes have 36% of total trips and active modes account for nearly 18% of commuting trips – 16.92% for walking and cycling for 0.19%, which is three times smaller than the national average (refer to Fig. 1 below). These figures become more unbalanced favouring the private car use if we consider the overall LMA. Clearly, there is an outstanding need to promote more effectively cycling, if this active mode is to be included in the political agenda of Lisbon's urban mobility. Besides its hilly characteristic in many parts of the city and a feeling of unsafety with respect to motorized modes, a main reason for Lisbon's lower modal share of bikes, is its incipient cycle infrastructures compared with other cities of similar size and with similar geographic characteristics. In fact, the purpose of a cycle network is to provide cyclists with safer and more convenient cycling mobility (Austroads Ltd et al., 2014).

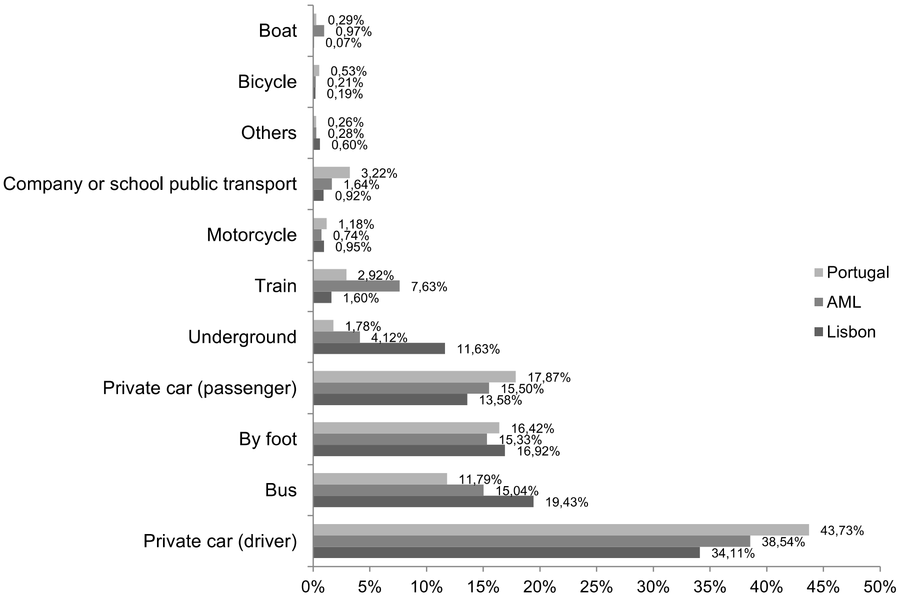


Figure 1. Modal share of commuting trips in Lisbon, LMA and Portugal (Source: INE, 2011)

Fig.2 shows the existing and operating cycle network (red links), but also those under construction (orange) or currently under study (yellows). The existing cycle network (78 km of segregated cycle paths) was planned and designed mainly for leisure trips between green parks, gardens and some touristic sites. These paths were included in Lisbon's 'green corridors', for example, along Tagus' riverside and in the western part in the Monsanto forest (lighter green area indicated in Fig. 2). Noticeably, the city lacks a more encompassing cycle network, namely in the central areas. Recently, the municipality of Lisbon announced a few projects with clear prospects of increasing the number of cycle lanes in the city centre, for instance linking the campuses of the University of Lisbon and in the plateau area of Lisbon (refer to the green rectangle in Fig.2), besides the launching of a bike sharing system by December 2016. Still, there is no provision of a clear and formal global cycling network plan, yet.

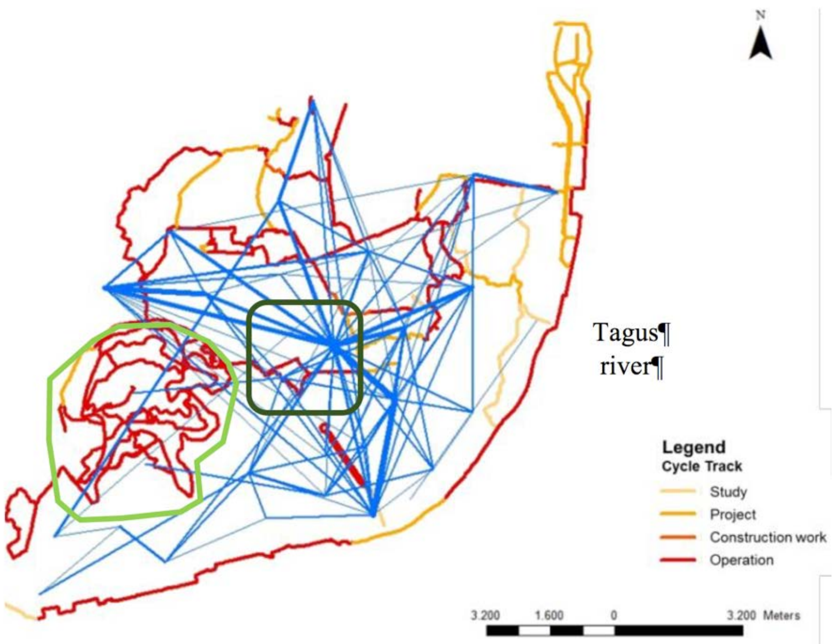


Figure 2. Demand desire lines and today's cycle network

The main problem is that the current network does not suit a significant number of cyclists' needs, namely those that use or are likely to use bikes for daily commuting (from home to work or to school). Fig. 2 illustrates the desire lines between the main OD pairs (blue lines) whose thickness varies with the number of total trips. It should also be referred that the central area of Lisbon, delimited by the darker green rectangle in Fig.2, concentrates the majority of jobs of the city and, as such, attracts the largest majority of commuting trips.

On the other hand, cycling activity is difficult to trace, as they are not intrinsically limited to road infrastructure and therefore are not necessarily captured by standard survey procedures, besides the very low modal bike share in Lisbon. In fact, this difficulty is generally recognized in the literature as the potential cycling demand is complex and must be addressed (Frade and Ribeiro, 2014). There are a few proposed methodologies that address this problem (Handy et al., 2014). Portuguese available bike statistics are solely based on the national census survey last performed in 2011, where citizens were asked which transport mode they would use to travel to work or to school. Other mobility surveys considered bike also, but somehow overlooked this mode (Santos, Martinez, Viegas and Alves, 2011). In fact, these are included in the broader category of active modes together with pedestrians.

The desire lines presented in Fig.2 result from the analysis of the origin-destination (OD) matrix estimated with a survey conducted in Lisbon in 2004 (CML, 2005) for 40 traffic assignment zones (TAZ) within Lisbon's municipality limits. This OD matrix corresponds to all trips between the 40 TAZ, during a working day. Hence, it serves as a surrogate indicator of the overall potential of generation and attraction of trips for all modes, including cycling if the required network is provided. As such, no differences are made regarding the trip motives and adequacy to travel modes. Although this was the data available for the present study, we recognize that over 10 years, mobility patterns change in a city such as Lisbon. However, the overall organization of the network and land uses did not change much ever since, and is expected to remain stable as typically consolidated areas are. Therefore, in relative terms, the desire lines are likely not to change significantly over the next decade. As such, screening the current road network to plan for a cycling network, based on this demand data, is acceptable.

Considering that complete (and thus reliable) information regarding cycle trips in Lisbon has not been collected, the values used relate to the total amount of trips for all motorized modes which enables the analysis of not only existing but also potential bike trips, not considering any mode splitting a priori. These desire lines correspond therefore to the potential for mobility interaction between all origins and all destinations. The longest distance between origins and destination within Lisbon's municipal borders is below 20km (using the shortest possible distance). 70% of OD pairs are less than 5km apart and, as such, are adequate to cycling. As referred above, formal cycling lanes and paths are lacking in many areas of Lisbon and, hence, not satisfying the main desired lines, especially the city center or for the OD pairs with higher number of trips (red cycle network in Fig. 2 is not covering the thickest blue desire lines towards the central areas). The fact is that if these are not met, cyclists will choose either other routes besides the fragmented existing cycle network, or other modes.

4. Methodology

4.1 Methodological approach

The methodology proposed here (refer to Fig. 3) aims to screen, at an early planning stage, the potential for rearranging the existing road network (carriageway) and accommodate a noteworthy cycling network in consolidated urban areas while minimizing the reduction of road network capacity for motorized vehicles. Considering that enlarging the carriageway is not feasible in many consolidated areas (like Lisbon), the only possibility is to reduce the existing road network capacity for motorised traffic, by narrowing existing lanes and include cycle lanes or paths. Further refinement of the potential cycle network obtained with this procedure is required, namely prioritising intervention according to the main desire lines, main generators and attractors of bicycle trips, and available budgets, before final selection.

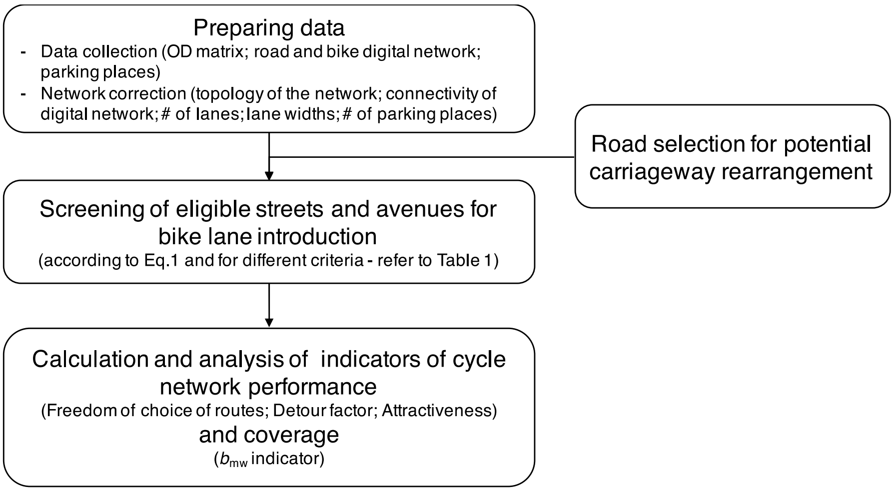


Figure 3. Methodological approach

The first step is to characterize the road network according to the following attributes: road hierarchy, average circulation speed and volumes (when available), number of lanes and corresponding width, and existence of parking places. Then, we defined the design criteria to rearrange the road network and include cycle lanes or paths, potentially. Based on this selection, each link is screened according to equation 1 (refer to section 4.3 below) and, if compatible, a cycle lane/path is included – one one-directional lane/path on each side of the road. After testing for compatibility with additional cycle lanes/paths, we analyse the quality of the final cycling network according to standard indicators used to assess network performance. As referred in the Australian guide for cycle network planning and design (Austroads Ltd et al., 2014), an appropriate cycle network should qualify positively to the following features: safety, coherence, directness, attractiveness and comfort. Furthermore, as referred in Section 2 before, the CROW design manual (2007) has suggested that cycle networks should aim to a maximum mesh width of 200 to 250 meters. This reference metric allows also to identify zones of an urban area with lower cycle network density – i.e., 'black spots' where a significant part of that zone is more than 250 meters apart from any cycling infrastructure. In section 4.4, we describe all performance indicators we analyse here.

In the present case study, the methodological approach is based on Lisbon Municipality's digital road network that was corrected and improved in a geographic information system (ARCGIS). The existing road network in Lisbon is divided into 5 levels of the hierarchy according to Lisbon's master plan (http://www.cm-lisboa.pt/viver/urbanismo/planeamento-urbano/plano-diretor-municipal). The 1st level corresponds to the structural network (major urban freeways), the 2nd to the main distribution network (principal distributors and arterials), the 3rd to the secondary distribution network (secondary distributors and arterials) and the two remaining (levels 4 and 5) to local distribution and access, respectively. This plan defines also the corresponding operational characteristics, including speed limits, parking places, bus stops, etc. (refer to Lisbon's master plan site: http://www.cm-lisboa.pt/viver/urbanismo/planeamento-urbano/plano-diretor-municipal). Accordingly, 1st level highways are not adequate for cycling. 2nd level streets/avenues should have separated cycle paths, while cycle lanes would be adequate for 3rd level streets/avenues. Finally, 4th and 5th levels are shared roadways which can be open to both bicycle and motor vehicle travel, since average circulation speed is below 30km/h and traffic volumes are below 1500vehicles/hour.

Tacking into account this classification, the screening procedure proposed here addresses only 2nd and 3rd level streets and avenues, considering that 1st level highways are not prone to bicycles and 4th and 5th level streets are shared roadways. Several attributes of the network were lacking and were collected, firstly, through an exhaustive verification of the network using Google Earth, and secondly, completed through fieldwork.

4.2 Criteria for road network rearrangement and cycle network definition

The basic screening criteria to evaluate the possibility of including cycle lanes ($N_{i,cycle}$), was the number of lanes (N_i) and corresponding width availability (L_i^j).

$$L_i^j \geq N_{i,road} \times LA_{min}^j + N_{i,cycle} \times LC_{min}^j \tag{1}$$

for each segment i, and minimuim width lane possible, LA^j_{min}, for motorized vehicles, or bicycles, LC^j_{min} (refer to Table 1).

We note here that we assume that $N_{i,cycle} \leq 2$ – one one-directional lane/path on each side of the road.

Table 1. Combinations of desirable and acceptable lane width criteria for cycle lane inclusion

Criterion	Road lane minimum width (LA_{min}) – in meters	Cycle lane minimum width (LC_{min}) – in meters
1	2.7	1.2
2	3	1.2
3	2.7	1.5
4	3	1.5

Source: adapted from Austroads Ltd et al. (2014)

As visible, there are two levels of requirements for both motorized vehicles and bikes: desirable (higher) and acceptable (minimum) values for single lane widths (for both motorised and bicycle roadways). If minimum values are to be included, there are negative consequences for road capacity due to lower circulation speeds (TRB, 2000) and, possibly, in terms of safety in the case of bicycles, as they get closer to other road vehicles. This is the trade-off that transport and urban planners have to analyse and plan for the overall network and after determining mobility policy targets regarding both the levels of service of the road network and the desired modal share of active modes for the city and, more specifically, for bikes. We recall that these criteria were evaluated for the 2nd and 3rd levels of the road network, only, and that they are extreme values. It is acknowledged that both 2.7m and 1.2m are narrow lanes for motorized vehicles and bikes, respectively. Intermediate widths can be tested for both cases – that is, between 2.7-3m and 1.2-1.5m for motorized vehicles and bikes, respectively.

Complementarily, we analysed the possibility of removing parking places in narrower road lanes in order to ensure cycle network coherence (refer to section 4.4 below, for the definition used here) and, eventually, increase the overall cycling network length. This analysis was performed on a case-by-case approach. The removal of these parking places can have an important network effect, by improving its connectivity (which is one important components of network coherence).

4.3 Indicators of cycle network performance

After drafting a cycle network based upon road network hierarchy criteria (according to the different 4 combinations of lane widths for motorized vehicles and cycling) and considering space requirements, the procedure proposed here is to refine the drafted network using performance indicators. As referred before, an appropriate cycle network should qualify positively to the following features (Austroads Ltd et al., 2014):

- Safety – as infrastructure should minimize risk of traffic-related injury, ensure low perceived danger, and minimize conflict with vehicles;
- Coherence – as infrastructure should form a coherent entity, have connectivity, be continuous, signed, consistent in quality, easy to follow, and have route options;
- Directness – as routes should be direct, based on desire lines, have low delay through routes for commuting, avoid detours and have efficient operating speeds;
- Attractiveness and Comfort – as routes should be safe, illuminated, integrated with surrounding area; have a smooth skid-resistant riding surface, standard widths, gentle gradients, avoid complicated manoeuvres.

Among these, our approach considered the following indicators:

- Freedom of choice of routes (FCR_i) for coherence, in the sense that the more cycle lanes/paths exist in a TAZ, the more options cyclists have to perform their trips – thus ensuring more route options.

The indicator was calculated using the following equation for each TAZ:

$$FCR_i = \frac{\sum_j l_{cycle,i,j}}{\sum_j l_{road,i,j}} \quad (2)$$

, where $l_{cycle,i,j}$ corresponds to length of connected and continuous cycle segments j of the zone i and $l_{road,i,j}$ the length of road segment j of the zone i. We note that cycle segments include the 4th and 5th level road segments. If FCR_i=1, then the road network of the TAZ can be fully used to cycle. If FCR_i = 0, then no road segment of the TAZ can be used by bicycles. With this indicator, the coherence of the cycling network depends on the coherence of the road network. Caution should be taken to test for the coherence of the road network beforehand. We argue that in consolidated urban areas, this is mostly often the case, since the road network development has stabilized.

- Detour factor (DR_i) for directness, which is the actual route length on the bicycle network divided by the Euclidean distance between the origin and the destination of a trip. The indicator was calculated using the following equation for between each OD pair:

$$DR_{ij} = \frac{l_{cycle,ij}}{l_{euclidean,ij}} \quad (3)$$

, where $l_{cycle,i,j}$ corresponds to cycle route length between i and j and $l_{euclideane,ij}$ the Euclidean distance between *i* and *j*.

- Safety, Attractiveness and Comfort were aggregated into an impedance index (I_j) for each segment of the cycle network according to the following equation:

$$I_j = \sum_i w_i \times \alpha_i \times c_i \quad (4)$$

where w_i corresponds to the criteria i used to quantify each indicator for the segment j, a_i corresponds to the weight of each indicator as calibrated by Felix (2012) through an internet survey to the population of regular bikers of Lisbon (commuters), and c_i corresponds to the cost of the link (measured in travel time – minutes).

The criteria used for each indicator were the following:

- Type of cycle segment for safety. As suggested by the Australian guide, safety can be characterized qualitatively on the basis of risk exposure. We considered that minimum risk exposure to road traffic would occur for 4th and 5th levels of the road hierarchy where traffic calming is expected. Maximum risk exposure was attributed to narrower cycle segments (1.2m) close to narrower road lane widths (2.7m). Intermediate risk was considered for the reminder cycle segments.
- Travel time for attractiveness of each segment. Although it is not suggested for attractiveness in the guides reviewed before, we opted for travel time since we are addressing utilitarian trips where travel time minimization is important. To quantify this indicator, we considered an average speed of 15km/h multiplied by the corresponding segment length.
- Grade for comfort of each segment. Topography is one major barrier to most cyclists and thus reducing the comfort of the trip when it increases, although we recognise that comfort is affected by other issues (e.g., climate, pavement, etc.). Quantification of grade was provided by available information in the GIS model (refer to Figure 5).

Finally, we we propose a new indicator β that measures the cycle network coverage for a 250m buffer width along the selected road segments (refer to the equation below), compared to total area analysed.

$$\beta_{mw} = \frac{\sum_s (l_s \times mw)}{A_{zone}}, subject\ to\ \beta_{mw} \leq 1. \qquad (5)$$

where l_s corresponds to the length of each segment of the cycle network that is multiplied by the mesh width, m_w, to calculate the equivalent area (references value of the mw can vary between 200m to 400m), and A_{zone} corresponds to the total area under analysis (which could the municipality of Lisbon altogether, or one TAZ only).

β_{mw} varies between 0 and 1, where the *absence of cycle network* would correspond to$\beta_{mw} = 0$, and the theoretical *ideal cycle network* would correspond to $\beta_{mw} = 1$, where any point in the zone analysed is at least a 200 to 400m apart from a cycle infrastructure, depending on the mesh width accepted for the analysis.

We calculated β_{mw} values for Lisbon and each TAZ of the Origin-Destination matrix presented in section3, before. As such, we could identify the TAZ with lower cycle network coverage (the "black spots" of the network). We also compared the cycle network coverage of each TAZ with the corresponding mobility demand, to verify whether a lower coverage is missing or just not necessary because users don't go there. To illustrate this compatibility of the cycle network with the demand, we built a graph where the x-axis corresponds to the total trips to and from each TAZ and the y-axis corresponds to the values of β. The graph was divided in 4 quadrants delimited by the 25th percentile of total TAZ demand and a β_{250}=50% (i.e., half of the TAZ locations are more than 250m apart from a cycling infrastructure). The "black spots" correspond to TAZ were demand is significant (above percentile 25) and were the cycle network coverage is below 50% (our assumptions).

The indicators included here provide an evaluation of relevant aspects perceived by bikers and important for city planners. As such, it brings important insights to the quality of the screened cycling network at an early stage of planning. Still, it is important to highlight that the finer indicators should be added to fully represent the real needs of users, as other network characteristics might be obstacles or barriers to cycling, such as crossings, traffic signalization, polluted areas, etc. In fact, bicycle route choice models include many of these aspects when simulating the perception of users (refer to Dill and Carr, 2003, and Broach et al, 2012).

Importantly, we refer that the indicators were calculated with the Network Analyst tool of ARCGIS for the cycle networks generated according to the different criteria defined. Still, isolated links were not considered, as they were not connected to the remaining generated cycle network, although they naturally arose because they met the lane width criteria, for instance all segments in roundabouts that are 4m wide.

Figure 4. Topography of Lisbon's road network

5. Results and discussion

5.1 Possible cycle network configurations

Fig.5a to 5d illustrate the road network segments allowing for the inclusion of additional cycle lanes according to different criteria for 2 and 3 level segments. As presented in Table 2, criterion 1 determines narrow lanes both for road and cycle networks and, thus, generates the more comprehensive cycle network of the network (Fig.5a) with 11% of network coverage, when compared to criterion 4 the more restrictive one – i.e., wide lanes for both road and cycling – leading to the more incipient (3%) and fragmented network (Fig. 5d). In between, criterion 2 and 3 generate quite fragmented networks, although Fig.5c is better by restricting more road lane width. We highlight that the quality of the network, depends on its performance that is analysed in the next subsection 5.2.

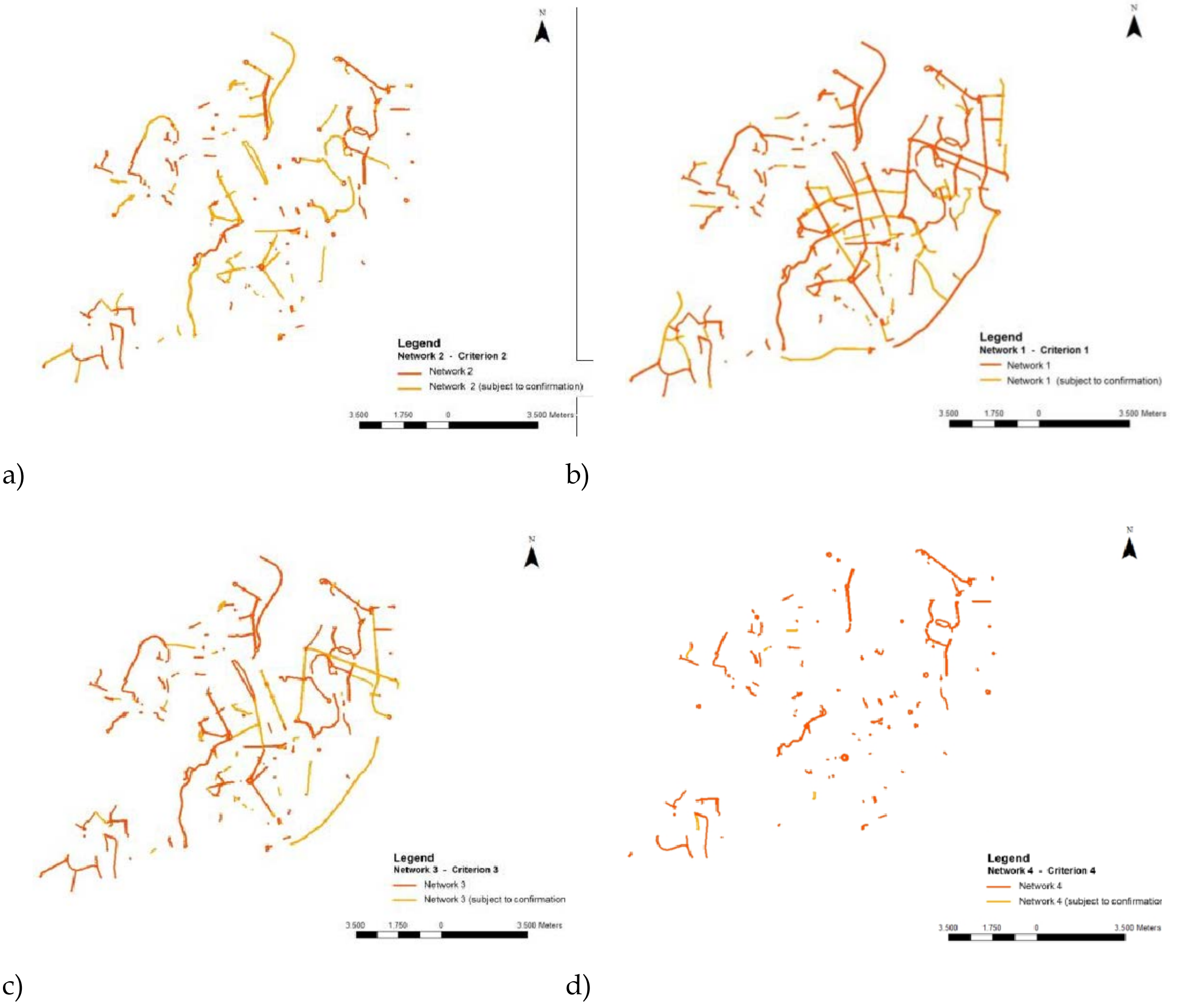
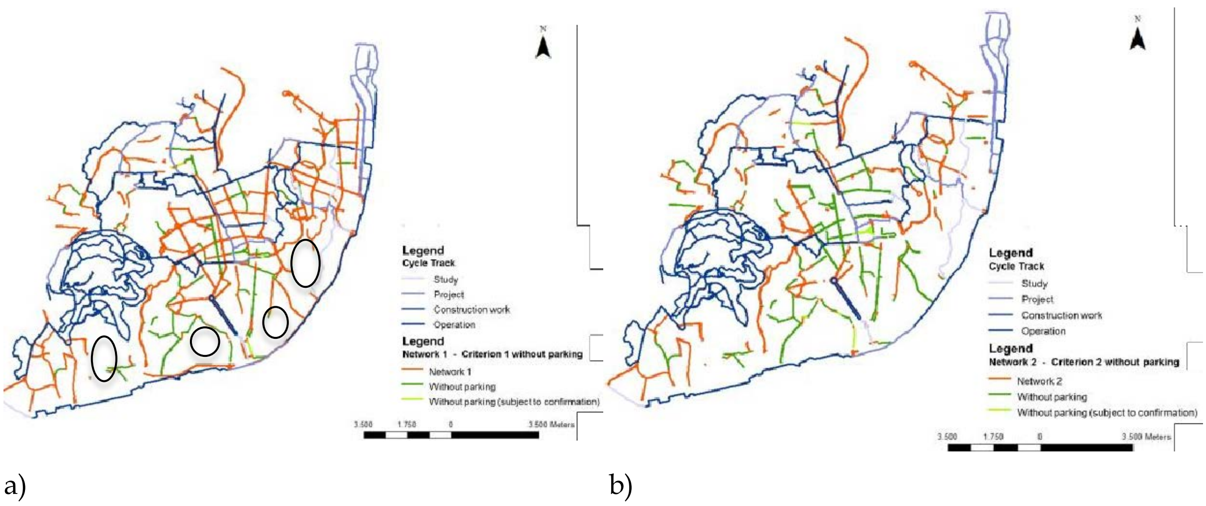
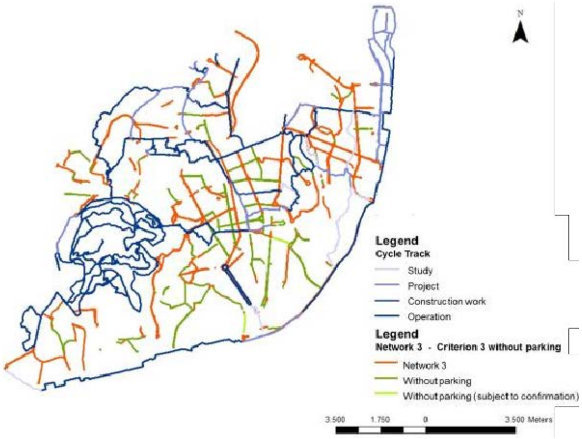


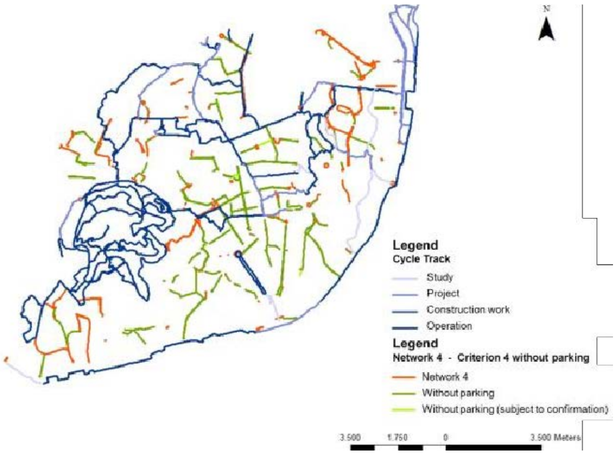
Figure 5. Road network rearrangement for cycle network according to different criteria: (a-d) for criteria 1 to 4, respectively

In these maps, the red lines illustrate the segments where cycle lanes fit while the orange lines show the segments where fitting an additional cycle lane is uncertain. In such circumstances, we verified the possibility to eliminate parking places in order to make it definitely possible. The corresponding results are shown in Fig.6a to 6d, for criteria 1 to 4, including thoughtful removal of parking places.





c)



d)

Figure 6. Road network rearrangement for cycle network according to different criteria: (a-d) for criteria 1 to 4, respectively, while removing parking places also

In addition, these figures include also the existing and planned cycle network by the municipality. As such, we can verify that only the more restrictive criteria for both road and cycle lane widths allows for a comprehensive cycle network implemented in the 2nd and 3rd level road segments. Still, Fig.6a identifies some areas that are lacking some coverage (circles in black – refer to section 5.2 for the procedure to identify "black spots" of lower cycle network coverage). These areas correspond to the hilliest zones of Lisbon (historical old quarters) whose road network includes 4th and 5th level segments, only, and that inherently include shared lanes although not very comfortable for biking due to higher grades. Importantly, these hilly locations can be addressed with specific technological solutions like lifts. The Trampe/Cyclocable in Trondheim (Norway, http://trampe.no/en/technology) was built with a capacity for 6 cyclists/min at a speed of 2ms. Alternatively, tramways have long existed in the older historical quarters of Lisbon to improve pedestrians' accessibility to the neighbourhoods of the castle of S. Jorge, Bairro Alto, and Torel. These tramways could be adapted to carry bikes uphill, like other public transportation solutions provide (for instance, bike forks on urban buses).

Table 2 presents the percentage of Lisbon's total road networks that could potentially be rearranged to include cycle lanes. It presents the results obtained for each cycle network that emerged according to each of the 4 criteria presented in Table 1, with and without parking places removal.

Table 2. Combinations of desirable and acceptable lane width criteria for cycle lane inclusion

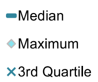
	Criterion			
	1	2	3	4
Without parking removal	11% *(368km)*	4% *(143km)*	7% *(234km)*	3% *(100km)*
With parking removal	17% *(568km)*	11% *(368km)*	14% *(468km)*	8% *(268km)*

These results suggest that more stringent intervention in the road network (i.e., narrowest widths for both road and cycle lanes with thoughtful parking removal) could generate a cycle network that would correspond to nearly 20% (which is the network coverage in Copenhagen, for example) and could reach nearly 600km of usable road network for cycling (including separate lanes, bike lanes and share lanes, altogether).

5.2 Performance of possible cycle network configurations

Fig.7a and 7b illustrate the descriptive statistics obtained for the indicators coherence and directness calculated with the criteria freedom of choice routes (FCR) and Detour factor (DF), respectively, for all cycle lanes and paths within (in the case of FCR) or between (in the case of DF) all 40 TAZ.

a)



b)

Figure 7. Descriptive statistics for a) Freedom of choice of routes – FCR (coherence) and b) Detour Factors – DF (Directness)

As expected, the cycle network obtained with "criteria 1 plus parking removal" is the highest, although "criteria 3 plus parking removal" follows close behind. As such, if safety and comfort are valued more by cyclists, then the former network should be preferred since it reserves 1.5m for cycle lanes. Interestingly, we notice that there is a high level of dispersion around the median, indicating that there are big differences of DF between TAZ. Lowest cases should be addressed separately for improvement. Overall, DF are acceptable ranging from 1.45 (for "criteria 1 plus parking removal") to 1.78 (for "criteria 4"), corresponding to the more (and less) direct cycle network where on average cyclist would perform less than 45% (or almost the double) than the corresponding Euclidean distance between OD pairs. Again, "criteria 3 plus parking removal" follows close behind with a DF of 1.47. Differences between TAZ are again big and maximum detour could be as big as 5 to 9 times the equivalent Euclidean distances for all criteria considered.

Fig.8 shows the impedance of the cycle network for the 2nd and 3rd level road segments. Impedance aggregates 3 different indicators: safety (based on cycle lane types and weighed α = 0.342, refer to Eq.4); attractiveness (based on speed and weighed α = 0.415); and comfort (based on grades and weighed α = 0.243) (refer to Felix (2012) for complete description of the weighing procedure). The impedance analysis of the potential cycle network obtained with criteria 1 plus parking removal suggests that, overall, it would perform well. Still, some segments have impedance values up to fourfold the lowest values calculated, where inconvenience strives mainly from steep gradients approaching the hilly old quarters of Lisbon (refer to the orange and red segments of Fig. 8). Still, these are a minority for which mechanical artefacts should be introduced to overcome such burdens. Elevators already exist in some parts that could possibly be adapted to bikes. Like referred previously, other solutions might as well be installed, following the example of the Trampe/Cyclocable in Trondheim, Norway.

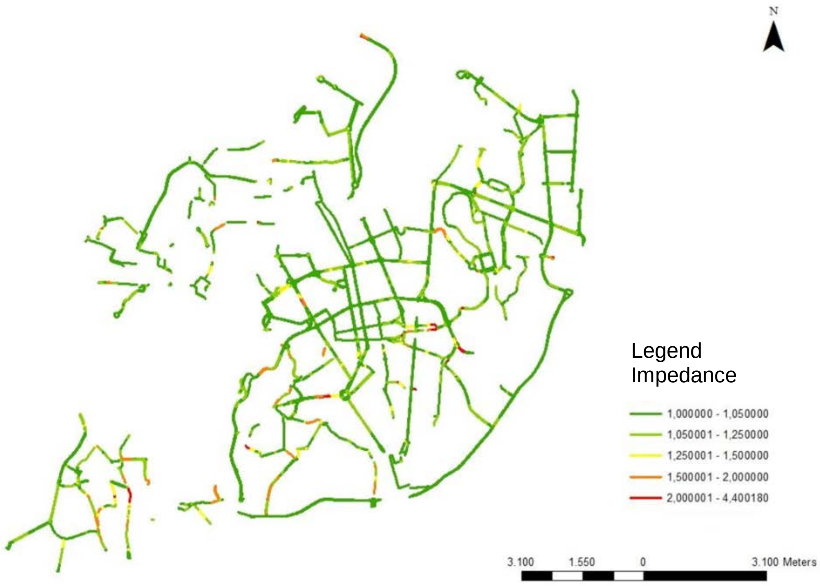
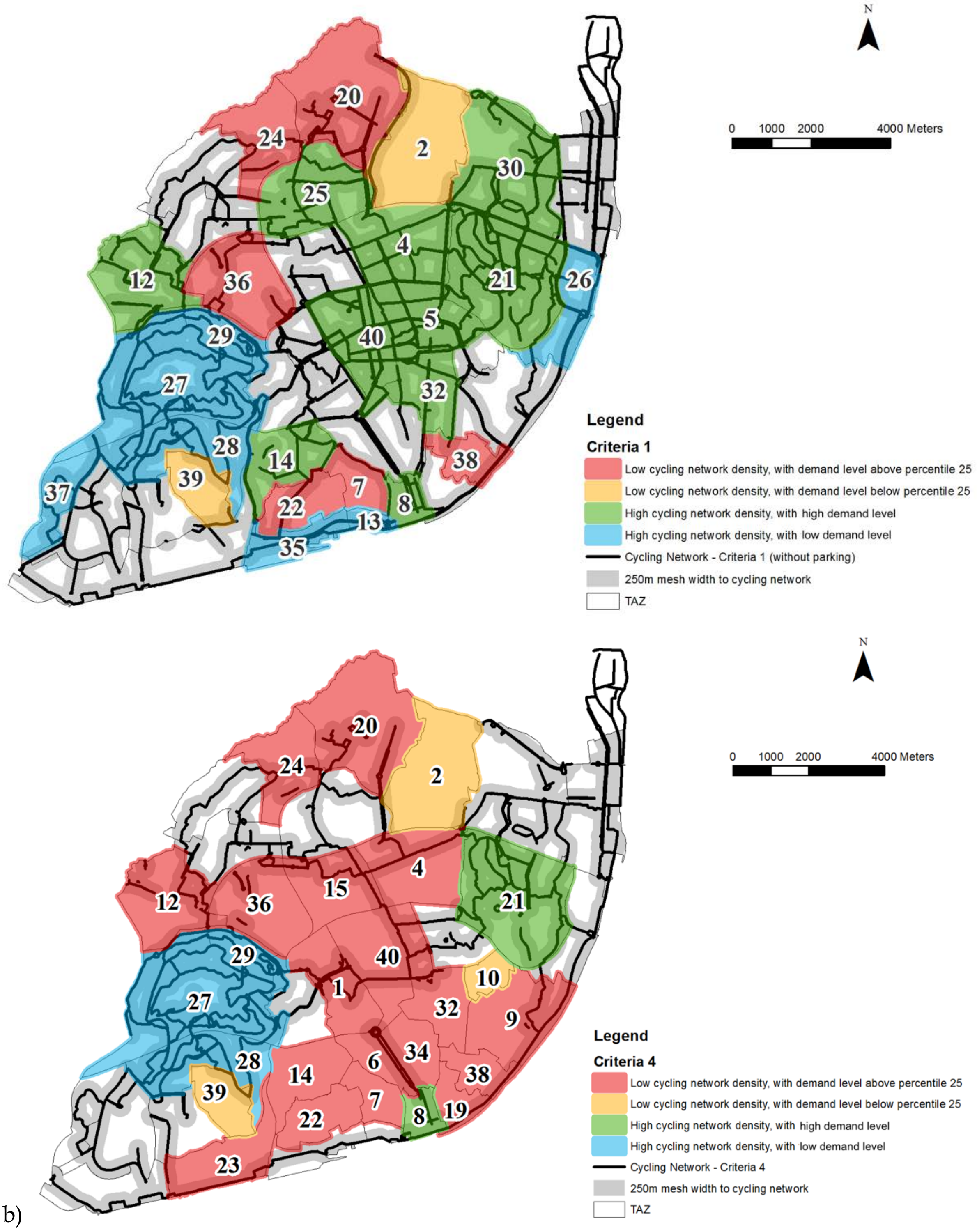


Figure 8. Impedance of the cycle network obtained with criteria 1 plus parking removal

Safety and comfort were the indicators that respondents weighed more in the study by Felix (2012). Still, we argue that topography is also a major barrier for the widespread cycling in Lisbon, besides the lack of a formal cycle network. Figure 4 (presented in section 4.4, previously) illustrates the grades of the road network of Lisbon and confirms that the large majority of the network (~73%) is below 5% grade and thus adequate to cycling and 54% is below 3%, and hence totally adequate for cycling. As such, the impedance analysis of the obtained cycle network could be used to prioritise an investment program for building the cycle lanes in the 2nd and 3rd level streets/avenues, combined with the principal demand desire lines of study area.

Finally, Figures 9a and 9b illustrate the extent to which the obtained cycling network is close to the theoretical ideal network. The grey areas correspond to the cycling network coverage if we accept that being 250m apart from a cycling infrastructure corresponds to an ideal network (CROW, 2007, PRESTO, 2010, SUSTRAN, 2014). These figures present the cycling network coverage obtained under the criteria 1 with parking removal and criteria 4 without parking removal.

a)



b)

Figure 9. Cycling network coverage for (a) criteria 1 with parking removal and (b) criteria 4 without parking removal

Fig.9a illustrates that most of the city would be either very adequately (green zones) or adequately (uncoloured zones) served with cycling network, under criteria 1 with parking removal. Visibly, the more stringent criteria 4, without parking removal, reduces to a large extent the coverage of the obtained cycle network. Corroborating with this conclusion, Fig. 10 presents the β_{mw} obtained for the municipality of Lisbon, using both the mw=250m and mw=400m. Results indicate that β_{250} =50% for criteria 4 without parking removal, while β_{250} =90% for criteria 1 with parking removal. Interestingly, if 400m access to cycle infrastructures is acceptable, results indicate that β_{400} =89% for criteria 4 (without parking removal), which is higher than the cycle network coverage with criteria 1 (with parking removal) for a mesh width of 2500m. However, in this case, the number of unserved areas would still be very high (not illustrated here).

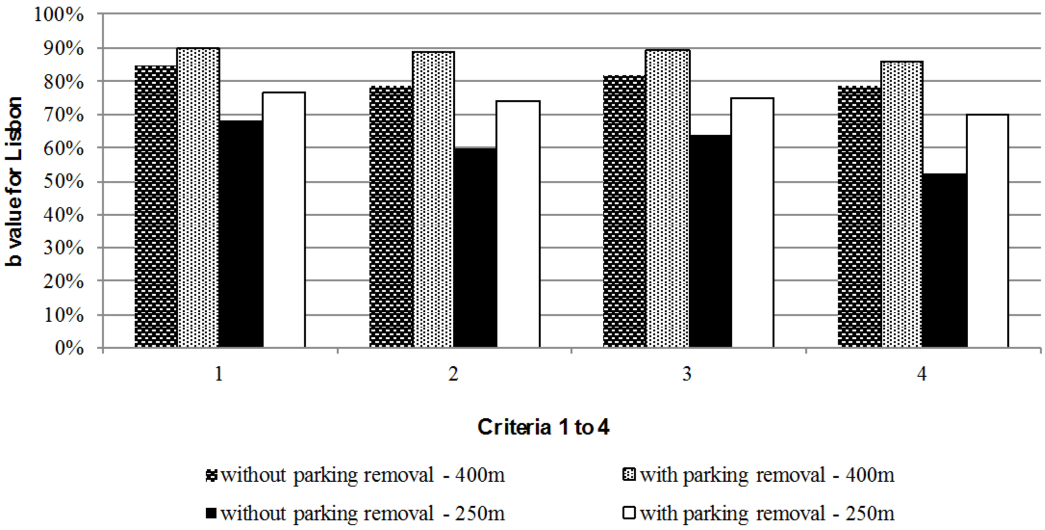


Figure 10. β values calculated for the municipality of Lisbon for 250m and 400m mesh widths

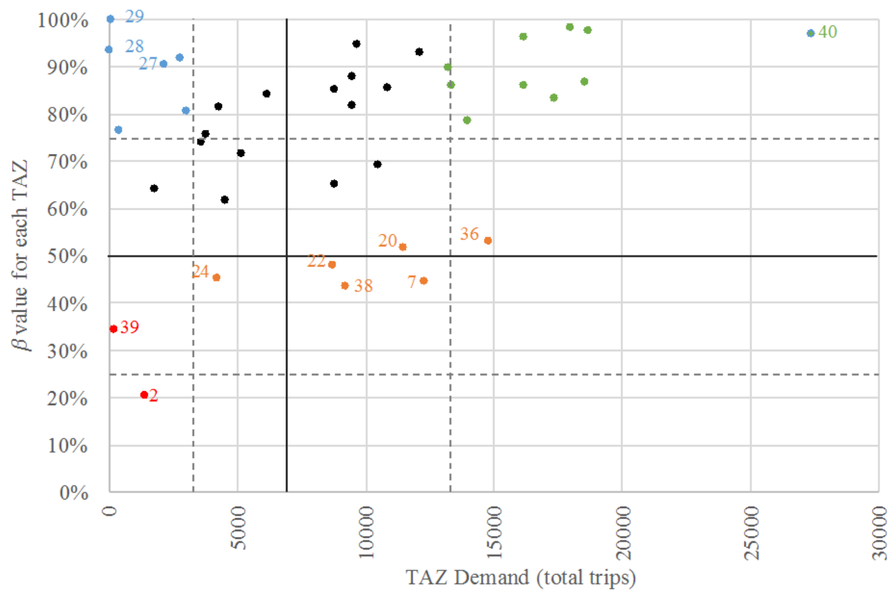
Fig.9 illustrates also the TAZ – *thinner black lines* – and identifies the TAZ that have:

- Low cycling network density (β_{250} < 50%) with significant demand (above Percentile 25) – *zones in red;*
- Low cycling network density (β_{250} < 50%) with insignificant demand– *zones in orange;*
- High cycling network density (β_{250} > 50%) with high demand (i.e., above Percentile 75%) – *zones in green;*
- High cycling network density (β_{250} > 50%) with low demand (i.e., below Percentile 25%) – *zones in blue.*

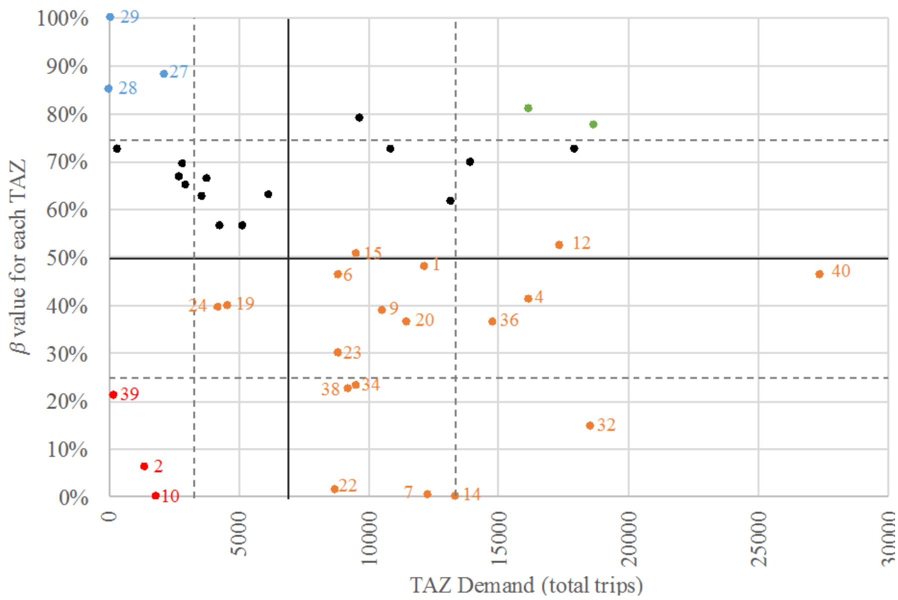
The *red* zones are considered the "black spots" because they have lower density cycling network although they show significant travel demand and, hence, a potential for shifting towards to cycling if the network is available. Fig. 11 below presents a straightforward graphical procedure to identify those "black spots" according to the assumptions presented previously: significant demand (above the percentile 25) with low cycling network density (β_{250} < 50%). Fig.11 indicates also the zone numbers presented in the maps in Fig.9. The zones in *blue* with high cycling network density and low travel demand correspond to the Monsanto forest of Lisbon where the majority of the bike trips are for leisure motives and not commuting that are captured in the OD matrix used here. Close to the river, zones 35 and 13 correspond to older quarters with many unoccupied buildings and low job density. Zone 26 was formerly an industrial zone of Lisbon with warehouses (most of them are not being used, today).

The upper-right quadrant of Fig.11a (*criteria 1 with parking removal*) groups the TAZ with higher travel demand (above Percentile 75) and high cycling network density (β_{250} > 50%).

The TAZ 40 presents the highest demand level (>27000trips for the morning peak hour) with a potential cycling network coverage with β_{250} = 97%, i.e. nearly full coverage. This TAZ is located in Lisbon's CBD and is a flat area (refer to Fig.4).



a)



b)

Legend: Solid black lines – Average values; Vertical dashed lines – 2nd and 3rd quartiles of TAZ total trips; Horizontal dashed lines – 25% and 75% of cycle coverage network per TAZ

Figure 11. TAZ demand vs. β values for (a) criteria 1 with parking removal and (b) criteria 4 without parking removal

According to the criteria 4 without parking removal, the lower cycling network density would increase 3-fold the number of "black spots" in the city, from 6 (15% of total zones) to 18 (45%) TAZ. Importantly as well, the number of green zones (i.e., high demand with high cycling network density) would decrease from 10 to 2. These are the trade-off consequences of requiring higher levels of service for both motorized vehicles and bikes (i.e., wider lanes for both modes).

5.3 Aggregate construction cost estimates

Finally, we estimated indicative construction costs to evaluate the feasibility of building the different configurations of the cycle networks. Table 3 presents the results obtained, where all unit costs are market-base and were obtained from Portuguese construction companies.

Table 3. Indicative construction costs of several cycle network configurations

Criterion	Thoughtful parking places removal	Total Cost (Million €)	
		Without taxes	With taxes (23%)
1	No	2.713	3.337
1	Yes	4.161	5.118
3	No	2.076	2.553
3	Yes	4.026	4.952

Assumptions of unit costs (for Portugal): Pavement paint = 5€/m2; Lateral lines paint = 0.5€/m; Horizontal signs paint (e.g., bike sign) = 30€/unit; Lane separation pillars = 15€/unit; Vertical signs = 70€/unit.

The assumptions used for these estimates were:

1. Painted pavement in a different colour (e.g., red), following the practice in New York, Portland, San Francisco, and Vancouver that have been painting some of their bike lanes bright green, blue, or red to enhance visibility and increase cycling safety, especially where conflicts between cars and bikes are most problematic (Pucher et al, 2011).
2. Separating painted lines for each lane;
3. Painting bike signs and/or arrows every 20m (as suggested Direction de la voirie de Grand Lyon, 2013);
4. Pillars installed every 2,5m on the left-hand side of the separated bike lanes; and,
5. Vertical signs at every intersection.

The overall budget varies between 2.6 million € and 5.1 million € (with taxes). We note that painting the pavement of all 2nd and 3rd level cycle lanes increases costs by 50%. Still, this is an important investment to improve the safety for cyclist, especially during the transition period from an incipient network where road drivers are not yet used to cyclists. As a reference for comparison, the budget for maintenance of Lisbon's road network pavements is 17 million euros, until 2017 – i.e., threefold bigger than the investment cost of building the most ambitious cycle network obtained here (although no maintenance costs are included nor the costs of rearrangement of the car parking places).

6. Conclusions

Our analysis suggests that the implementation of large cycle network can be implemented ubiquitously in the city of Lisbon despite its hilly, dense and consolidated urban fabric that have to be addressed with more specific solutions (e.g., elevators or other mechanical artefacts). In fact, the configuration and extension of the network resulting from the introduction of cycle lanes in the current road network is feasible by reducing the lane widths of 2nd and 3rd level segments, at acceptable costs when comparing to potential positive external impacts deriving from motorized traffic transfer. As expected, the best network obtained in terms of coherence and directness was determined by minimum lane width criteria for both road and cycle lanes. The downturn is that road capacity is hindered as speed is lowered due to corresponding lane width reduction. More research should be developed to analyse the extent of the impact and respective level of service. We note that opting for larger lane widths would increase levels of service and safety for cyclist. Nevertheless, this would come out at the cost of less connected and direct cycle network, i.e. with a worse overall network.

Comparing the cycle network with the desire lines of the demand for the more important OD pairs, only the networks with minimum lane width would satisfy the requirements of commuting trips of current and potential users. The mean values obtained in terms of detour factor show that the network obtained allows the connection, almost in a direct way, for the main OD pairs. We note that removing parking places along the roads to widen the space for cycle lanes would enable much better results when compared to the initial ones, yet again, at the cost of less space for motorized vehicles. It would also present significant advantages in terms of coherence by reducing the fragmentation of the cycle network.

Finally, network construction costs were evaluated for several configurations suggesting that total costs could be lower than 5 million € (including taxes), which is the amount obtained for the larger cycle network – i.e., narrower lanes for both road and cycle network and removing parsimoniously parking spaces. This is rather low when compared with the 17 million € budget for maintenance of Lisbon's road network pavements, until 2017. As such, this research suggests that cycle networks can grow from an incipient to large networks in consolidated urban areas without having to compromise excessively the level of service of the road network, and at acceptable investment costs. Yet, future research should develop this methodology by optimizing the network not only from a supply side but also demand-based by connecting first the main OD pairs with higher volumes of trips. For that, a finer demand survey is required to evaluate the potential bike trips within Lisbon. Furthermore, the network should be build incrementally. As such, a methodology for prioritizing the road carriageway adaptation for cycling should be developed to ensure an effective transition between the current network to a more ubiquitous.

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