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A Planning Practice Method to Assess the Potential for Cycling and to Design a Bicycle Network in a Starter Cycling City in Portugal

Fernando Fonseca *, Paulo Ribeiro and Carolina Neiva

Centre for Territory, Environment and Construction (CTAC), University of Minho, 4800-058 Guimarães, Portugal
* Correspondence: ffonseca@civil.uminho.pt; Tel.: +351-253-510-200

Abstract: There is growing recognition of the potential for cycling to provide more sustainable and active urban mobility. In Portugal, the National Strategy for Active Mobility aims at increasing the bicycle modal share from the current level of below 1% to 10% by 2030. This paper describes a planning practice method to assess the potential for cycling and to design a bicycle network in Ponte de Lima, a small starter Portuguese city, which only has some disconnected cycle lanes. The method consists of assessing the target population and target area attributes through a Geographic Information System (GIS) and Space Syntax operations. Results showed that the potential for cycling in Ponte de Lima is hindered by the hilly terrain, by the low population density and by the low percentage of the young population. The compact urban structure and the level of street integration enhances topological proximity and makes using a bicycle convenient. The proposed bicycle network comprises segregated cycle lanes, colored cycle lanes and a set of streets where cycling coexists with other road users. Adopting complementary measures, such as traffic calming and bicycle-sharing services, could be decisive to make cycling more appealing in Ponte de Lima and to help the city in reaching the ambitious goal of the National Strategy for Active Mobility.

Keywords: cycling; bicycle network; starter cycling cities; active travel; sustainable mobility

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1. Introduction

Cycling has come into focus for urban and transport planning as a solution to tackle several urban problems. When compared to motorized modes, cycling consumes fewer non-renewable resources, and reduces the emission of CO_2, air pollutants and noise [1–3]. Infrastructure for bicycles also causes less severance and requires less space than infrastructure for cars [4]. Bicycles also support higher passenger flows per surface, which helps in reducing traffic congestion [5]. Cycling is also an active travel mode and a way of undertaking physical activity, with well-known health benefits, contributing, for example, to reducing obesity, cardiovascular diseases, diabetes and stress [2,6]. Cycling is much cheaper than motorized modes in terms of infrastructure, it reduces health care costs, improves work productivity and is a relatively accessible mode of transport [1,7].

Cycling is particularly well suited for replacing car trips in central urban areas [8,9]. As an independent mode of transport, bicycles are recommended for distances up to 5 km or travel times up to 20 min. For these short urban trips, bicycles are faster than walking and other motorized modes [10,11]. For longer trips, bicycles can be used in combination with other modes of transport, including public transport.

Due to the overall benefits of cycling, many countries around the world have been adopting a wide variety of bicycle-friendly measures to encourage travelers to cycle regularly [12–14]. In the European Union (EU), the cycling modal share (daily commuting) varies significantly from country to country, ranging from 1% or less in Portugal, Cyprus and Malta to up to 36% in the Netherlands [15]. In addition to other reasons, the prevalence of a driving culture associated with the lack of cycling facilities is often cited as a critical barrier preventing people from cycling more in some countries [15]. As part of the efforts to create more bicycle-friendly environments, few cities and countries have been able to integrate cycling as a relevant mode of transport in their urban traffic systems. As noted by Dimter et al. [16], in many cases, cycling is mostly a leisure activity rather than a daily mode of transport.

Starter cycling cities are cities where the cycling modal share is residual (below 10%), and thus have no cycling tradition, limited expertise in developing cycling strategies and poor cycling conditions [17,18]. These cities are also known as "beginner cycling cities" [19] and "hostile cycling cities" [20]. With a cycling modal share of 0.6% in 2021 [21], Portugal is one of the EU countries where bicycles are less used as a daily mode of transport. For that reason and with few exceptions, most cities in Portugal are starter cycling cities [22]. Aiming to decarbonize the transport sector and reduce physical inactivity levels among people, the National Strategy for Active Mobility, launched in 2019 by the Portuguese Government [23], aims to reverse this trend. The National Strategy aims at increasing bicycle trips from the current level of below 1% to 10% by 2030. To achieve this ambitious goal, the Strategy will focus on integrating planning, education and traffic policies to encourage people to cycle more regularly.

The main objective of this paper is to present a planning practice method to assess the potential for cycling and design a bicycle network in Ponte de Lima, a starter cycling city located in the north of Portugal. The potential for cycling and for planning a bicycle network includes the target population and target area attributes. The first group includes demographic attributes that affect the propensity to cycle (population density and age). The second group includes built environment attributes that exert influence on cycling (slopes, street hierarchy, geometry of the street network and proximity to community facilities). These attributes are assessed by performing GIS and Space Syntax operations. The contribution of this paper is to demonstrate how to evaluate the potential for cycling and design a bicycle network in a starter city. The described method can potentially help planners and decision-makers in other similar starter cities to create more bicycle-friendly cities. It could be particularly useful for helping small Portuguese starter cities to reach the goal defined by the National Strategy for Active Mobility. For researchers, this paper tries to fulfil the following four gaps identified in the literature: (i) promote the use of bicycles in starter cycling cities, since most of the research focuses on cities with an established growing cycling culture [17]; (ii) provide a planning support approach for planning starter cycling cities [22]; (iii) explore the relationship between the built environment and cycling for transport, which has been insufficiently studied [24]; and (iv) fulfil the lack of studies in planning cycling networks [13]. For planners and decision-makers, this paper provides comprehensive information on various measures for cycling promotion in starter cities. With this case study, we tried to provide practical know-how and an initial spatial approach to address the specific problems and needs of this city that can lead to the development of more effective strategies for cycling promotion.

2. Background

Although there is no universally accepted definition, a bicycle network could be understood as a set of heterogeneous streets where cycling is not prohibited that provide various comfort and convenience levels for cyclists [25]. Accordingly, a bicycle network includes not only separated paths exclusively designed for the use of cyclists but also shared paths, where cyclists and other road users share the same space.

Planning and assessing bicycle networks are not simple tasks due to the multiple dimensions and attributes that influence bikeability, e.g., the extent to which an environment is convenient and safe for cycling [25]. Most of the assessment methods available in the literature are either location- or facility-based methods [5,26]. Location-based methods focus on the convenience of a location to be reached by bicycle and on predicting the level of demand for cycling in a specific area. In turn, facility-based methods focus on planning and evaluating the conditions provided to cyclists, namely by evaluating the suitability of facilities for cycling [26,27]. These assessment methods can rely on qualitative evaluations, quantitative analysis or both. Qualitative evaluations are always based on individual perceptions collected through questionnaires, surveys and focus groups, among other ways. These evaluations have been conducted for different reasons, namely to understand the cyclists' perception of cycling infrastructure and specific criteria [26,28], to score the relative importance of specific attributes on cycling [13,29,30], to analyze the relationship between the perceived built environment and cycling [24], to examine route choice [31,32], the suitability for cycling and the behavior of cyclists and drivers [33], among others.

In turn, quantitative evaluations are mostly based on objective evaluations of a set of attributes with influence on cycling or by developing indexes to measure bikeability [34]. Attributes have mostly been evaluated through spatial analysis, by using GIS and multicriteria tools. This includes, for example, the study of Tralhão et al. [35] for designing cycling suitability maps for hilly cities, the research of Terh and Cao [13] for planning cycling lanes and the study of Saplıoğlua and Aydınb [31] for choosing safe and suitable bicycle routes. In the second case, bikeability is estimated through indexes, which are composite measures of various built environment attributes [34,36]. In this case, the various attributes are weighted and then the points are combined to calculate a score that classifies the cycling conditions [37]. The bicycle level of service [38] and the bicycle compatibility index [39] are two classical examples of these indexes. Over the last years, many other bikeability indexes have been developed to evaluate the suitability for cycling [29,30,40] and to plan bicycle facilities [41,42].

If bikeability depends on various built environment attributes, which ones are those attributes? The literature indicates that safety, comfort, directness, cohesion and attractiveness are the most relevant dimensions that should be considered when planning a bicycle infrastructure [29,43,44]. In the EU, in 2018, 2160 cyclists died in traffic collisions, while 32,000 were seriously injured [45]). Safety is often considered an undeniable basic requirement for cycling [13] and a major determinant in choosing a route [27]. Fear of traffic is an often-cited reason for not cycling [46], particularly among women and children [33]. The provision of separated cycle lanes improves safety by limiting the conflict between cyclists and other road users [6,8,32]. Adopting traffic calming measures [1,2] and reducing conflicting trajectories [47] also help to increase cyclists' safety. Traffic speed, traffic volume, road width, street lighting, the type of intersections and the number of accidents are among the most used attributes to describe safety.

Comfort has mainly been described in terms of providing enjoyable, smooth and relaxed cycling experiences [44,48]. Cycling on irregular surfaces, pavements with bad material or in poor condition is often considered tiresome and stressful, which makes cycling less comfortable [44,48]. Slopes also have a significant influence on comfort, as small positive increments in slopes decrease travel speeds and increase the effort required to pedal [32]. There is evidence that people prefer to cycle in flat areas [12,41]. Slopes (uphill gradient) between 0% and 3% are considered and evaluated as the most suitable [49], while slopes above 5% are not recommended for cycling [8,35]. Thus, the type of pavement, the quality of pavement, slopes, cars parked on streets and the presence of curbs are some of the most used attributes to describe comfort.

Directness means that a bicycle network should provide direct routes between origins and destinations. As bicycles are human-powered, cyclists prefer direct routes to destinations and usually avoid large detours [2]. Detours reflect the distance between two points on the network, divided by the distance as the crow flies. A detour factor higher than 1.3 is considered excessive for cycling [2]. Directness also has a strong impact on travel time, as excessive detours require more time to reach a destination. Street intersections at which a cyclist does not have right of way and has to stop may also increase travel times. Their negative effect could be minimized by giving right of way to cyclists, by providing central traffic islands and remote cyclist detection at traffic lights [44]. The distance between intersections, travel time, the number of intersections per km and the stopping frequency per km are some of the attributes adopted to describe directness.

Cohesion shows the extent to which cyclists can easily cycle between their origin and destination. To be cohesive, a bicycle network should provide similar routes and conditions throughout the network, so that cyclists can easily follow it, have minimal interruptions requiring stops, such as crossings and traffic lights, and have good connections with public transport [2,43,44]. The CROW manual [43] also recommends that in a cohesive network, people should not have to travel more than about 250 m to reach the bicycle network. The presence of uniform pavements, signposting and the number of interruptions along a route are among the different attributes used to describe cohesion [2].

A bicycle network should also be attractive. Attractiveness is a critical attribute for cycling [13] but has been differently described. For some authors, attractiveness has been linked to visual and aesthetic aspects of the built environment [44], as well as to the presence of lively and mixed uses such as shops, restaurants and cafes [43,50]. For others, attractiveness refers to the provision of cycling infrastructure and facilities [27,33,51] or, more broadly, to the provision of secure and illuminated routes, having smooth skid-resistant riding surfaces, standard widths and smooth slopes [8]. Thus, attractiveness has been described through the built environment and cycling facility attributes. The presence of bicycle facilities, the width of bicycle paths and the number of trees along the routes are some of the attributes used to describe attractiveness.

In addition to the built environment attributes, it is also important to consider demographic factors. Variables such as population density, age, gender, education and socioeconomic status shape individual mobility and cycling. For example, evidence from previous studies indicates that higher population densities are related to higher cycling rates [52,53]. Age is considered one of the most important variables for identifying population segments more willing to cycle [18]. While in cities with high cycling levels, the influence of age is less notorious, as cycling is popular among all age groups [24,54,55], in starter cities, cycling tends to be more frequent among younger groups [17]. The physical effort required to pedal and the perception of safety make cycling less attractive for aged groups. Other studies indicated that in general, women cycle less than males and are more constrained by traffic hazards [53,56], while higher education increases the propensity to cycle [24,55].

To sum up, this background shows that the extent to which an environment is bicycle-friendly depends on various dimensions and attributes. These reflect not only the diversity of conditions provided to cyclists but also the different cycling cultures and the distinct subject areas that study this topic.

3. Methodology

3.1. Case Study

Ponte de Lima is a small city located in the north of Portugal (Figure 1). The city was founded in the 12th century and is distinguished by the medieval architecture of its historical center, shaped by irregular and narrowed streets and by the Lima River. According to Portugal Statistics, the municipality has an area of 320.25 km^2 and a population of 43,498 inhabitants [57]. The study area (Figure 1) comprises the city center located on the south side of the Lima River and the settlement located on the north side of the river. The two settlements are connected by two bridges. The stone bridge, which was originally constructed by the Romans, is one of the ex-libris of Ponte de Lima. The study area has 265 ha and around 5000 inhabitants [57].

The municipal modal share had the following distribution: cars (61%), motorcycles (1%), buses (25.4%), walking (11.9%), bicycles (0.3%) and other modes (0.4%) [21]. Although not reflecting solely urban trips, these statistics clearly indicate that mobility was strongly dependent on car trips. The residual cycling modal share can be explained by the lack of a formal cycle network, but also by cultural reasons, namely by the resistance to traveling by bicycle as found in other Portuguese cities [18]. The existing cycling facilities and the existing bicycle-sharing service are mainly devoted to recreational purposes. Ponte de Lima has four recreational cycle lanes along the two margins of the Lima River, which provide about 35 km of traffic-free routes, offering outstanding scenery views (Figure 2A). For transport purposes, the city only has a cycle lane built in 2021 during the requalification of the national road EN203 (Figure 2B). This lane has an extension of 3.3 km and connects some facilities but does not provide any bicycle access to the center and, more importantly, is not integrated into a cycling network. Thus, Ponte de Lima is a typical example of a starter cycling city, having a residual cycling modal share and an incipient cycling infrastructure.

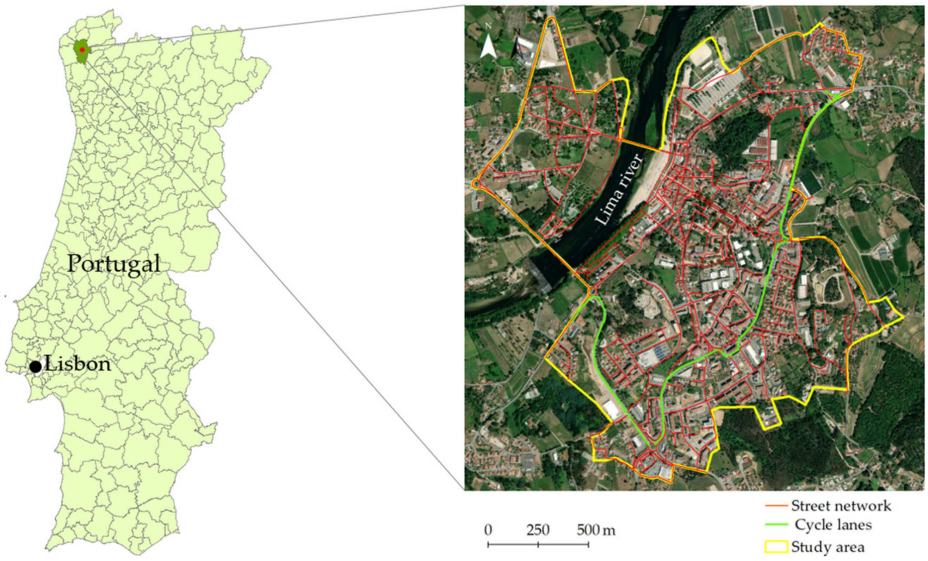

Figure 1. Location of Ponte de Lima and the study area.

Figure 2. Existing cycle lanes for recreational (**A**) and for commuting purposes (**B**) in Ponte de Lima.

Selecting Ponte de Lima as a case study is justified by four main reasons. First, the small size of the city makes the bicycle an alternative mode of transport as urban trips under 5 km can be considered the most suitable for cycling [9,58]. Second, the city has a wide range of urban characteristics, namely in terms of topography, urban tissue and street layout, which makes it challenging to plan a cycle network in this city. Third, Ponte de Lima is a typical example of a starter cycling city, where mobility is strongly supported by cars. Fourth, because the municipality is committed to making mobility more sustainable, namely by promoting the use of the bicycle as a daily mode of transport. The planning practice method described in this paper could help the urban planners of Ponte de Lima and other similar starter cities by providing initial guidance in the development of integrated strategies that goes further than implementing isolated measures, such as the construction of disconnected and sparse cycle lanes.

3.2. Defining the Potential for Cycling

The potential for cycling shows the extent to which a city with a residual cycling modal share may increase its cycling levels [18]. Assessing the potential for cycling is seen as a first step to supporting the adoption of planning policies that could make cycling accessible or even irresistible [1]. The potential for cycling could be evaluated by a changeable number of explanatory dimensions, although the built environment and demographic attributes are considered the most critical [17]. Considering the incipient cycling infrastructure for transport purposes found in Ponte de Lima, the assessment proposed in this study is based on (i) target population attributes, e.g., the amount and distribution of population with a higher propensity to cycle; and (ii) target area attributes, e.g., the conditions provided by the built environment for cycling.

3.2.1. Target Population—Demographic Attributes

The proposed approach to assess the potential for cycling in a starter city includes demographic attributes known for influencing the propensity to cycle [18]. According to the Background, two demographic attributes were selected: population density and age. This demographic information is usually helpful for defining long-term strategic solutions to attract cyclists of specific user groups [20].

- Population density: high population and residential densities mean a larger number of people living in a given area, creating the necessary critical mass to provide closer neighborhood destinations, such as bus stops and community facilities [59]. Thus, the effects of density on using bicycles could be at least indirect, because a higher density is often related to higher destination accessibility [60]. In this study, population density will be calculated as the number of inhabitants per hectare (ha) in each statistical tract through GIS operations, by using Census data [57].
- Age: the most significant demographic variable with influence on cycling is age [18]. In starter cities, cycling tends to be more frequent among younger groups and students, and so the target age for this study is the groups aged 15–29 years old [17]. Population age data will be retrieved from the Census [57].

3.2.2. Target Area—Built Environment Attributes

The proposed approach to assess the potential for cycling also includes built environment attributes. According to the Background, the built environment attributes selected were slopes (to describe comfort), street hierarchy (to describe safety), geometry of the street network (to describe directness and cohesion) and proximity to community facilities (to describe attractiveness).

- Slopes: topography has often been used to describe the level of comfort. There is a negative correlation between hilliness and cycling due to the additional physical effort required for climbing hills [17,18]. Although the problem of hilliness could be mitigated through urban design solutions, such as areas to allow cyclists to rest, or by using electric bicycles, slopes below 3% are considered the most suitable and attractive for cycling [35,49]. In turn, slopes greater than 5% are not recommended, as climbing such an ascent is difficult for many cyclists [35,61]. In this study, slopes were evaluated according to three levels: (i) low slopes ($\leq$3%) are considered entirely suitable for cycling; (ii) medium slopes (>3% and $\leq$5%) are classified as not very suitable for cycling; and (iii) high slopes (>5%) are considered not suitable for cycling. Average street slope data will be retrieved from Google Earth by estimating the difference in elevation between the endpoints of the streets/segments divided by the difference in distance between them.
- Street hierarchy: as conducted in previous studies [56,62], street hierarchy was used as a proxy of traffic speed and volume to describe traffic safety. In Portugal, as mentioned by Faria et al. [63], streets are organized into the following four hierarchical levels: (i) arterial roads: these are major regional and inter-regional roads that carry large

traffic volumes (more than 15,000 vehicles daily) allowing high traffic speeds (90/120 km/h); (ii) main distributor streets: these carry traffic between municipalities and connect the arterial and remaining streets, having moderate traffic volumes and speeds (between 6000 and 15,000 vehicles daily and speeds between 50/90 km/h); (iii) local distributor streets: these ensure traffic within urban spaces carrying no more than 6000 vehicles daily at no more than 50 km/h; and (iv) local access streets: offer mainly land access service (access to residential and commercial areas, public spaces, car parking, etc.), carrying no more than 3000 vehicles daily with maximum speeds that could be lower than 50 km/h. Except for the arterial roads where cycling is not allowed, riding a bicycle on main streets presents a risk of accidents much higher than when riding on local access roads [56,62]. Apart from arterial roads, the remaining types of streets can be found in the study area. Street data will be provided by the municipality.

- Geometry of the street network: the geometry of the street network has been used to describe route directness and the level of cohesion in cycling networks. Intersection density has been the most used attribute to describe the geometry of the street network [26,40]. Although streets with more connections may provide more alternative routes, shortening distances to destinations, they may involve safety risks (more crossings) and additional travel times when cyclists have to stop at intersections. For this reason, in this study, the geometry of the street network was estimated using a Space Syntax measure of street integration, which shows how easy it is to access a specific street segment from all other street segments based on the number of turns, e.g., the topological distance [53,64]. More integrated street segments require fewer turns and are more direct than less-integrated segments. Thus, integration is not about a metric distance between segments but is the sum of turns required in moving from one segment to another. The rationale for evaluating this attribute through Space Syntax was (i) the evidence that places with more integrated routes have more cycling activity [53,65]; and (ii) the need to take more Space Syntax measures on cycling evaluations [65]. In this study, the DepthmapX v0.8.0 software will be used to calculate street integration by considering a buffer of 2500 m, which corresponds to 10 min cycling and allows it to cover the entire study area.
- Proximity to community facilities: this indicates the extent to which the presence, proximity and diversity of community facilities make cycling convenient. Proximity to this kind of destination has been correlated with cycling [13,24,26,50] as mixed land uses shorter travel distances between origins and destinations, making cycling more attractive and convenient. In this study, and considering the characteristics of the study area, the following six community facilities were selected: (i) transport facilities (bus station); (ii) education facilities (schools and university); (iii) health facilities (hospital); (iv) security facilities (police station); (v) municipal government facilities (town hall); and (vi) urban parks. According to the literature, cycling distance is critical to access these types of destinations. It has been shown that destinations up to 5 km have more chances to be accessed by bicycle than those located at greater distances [9,66,67]. Data from community facilities will be extracted from OpenStreetMap to identify and map the location of these points of interest in GIS software.

4. Results

4.1. Assessing the Potential for Cycling—Target Population

The propensity of the population to cycle was evaluated according to the population density and the people between 14–29 years old. Figure 3 shows the distribution of these two attributes at the level of statistical tracts. For the sake of convenience, tracts within the same class values were dissolved.

The population density is relatively low (18.8 inhabitants/ha), ranging from 1 up to 197 inhabitants/ha. The most densely populated areas correspond to residential areas with a high building density, such as those located in the historical center and in some residential blocks around the center (Figure 3A). In turn, the areas with low densities can be found at the fringes of the study area, especially in the north sector, where the presence of single-family dwellings, usually with one or two floors, prevails. Around 65% of the area has a density lower than the average density (18.8 inhabitants/ha).

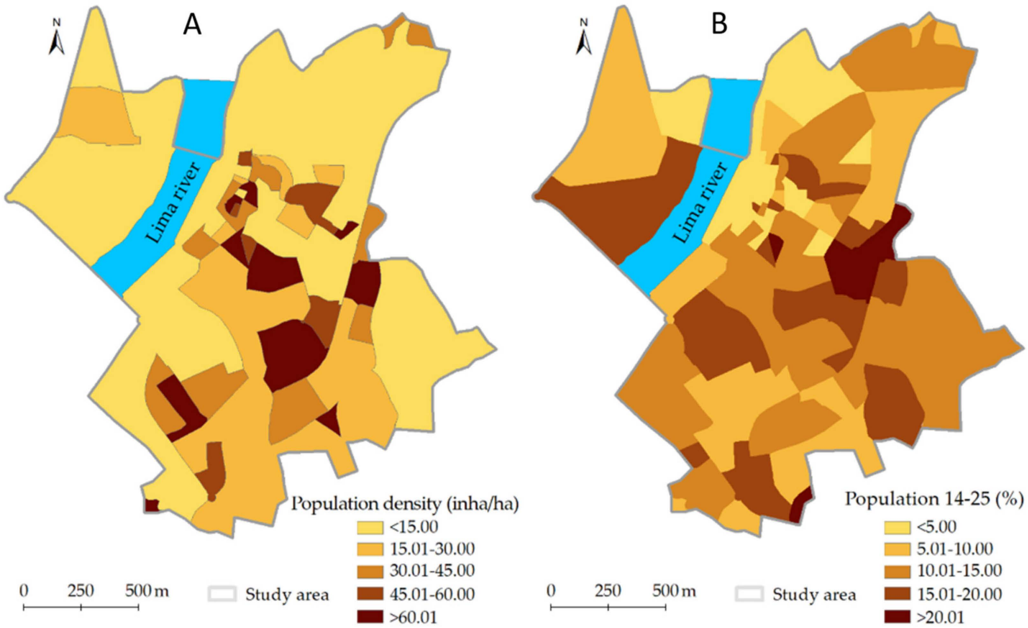

Figure 3. Population density (**A**) and population aged between 14–25 years old (**B**) in the study area.

Regarding the second attribute, the percentage of individuals aged between 14–29 years old was around 18%. According to the Census [57], the population living in the study area was mainly adults aged 15–64 years old (64.7%), but the percentage of seniors >65 (19.8%) was slightly greater than the percentage of individuals aged between 14–29 years old. The areas with a higher proportion of individuals aged 14–29 years old can be found in residential blocks located around the city center (Figure 3B). Thus, in terms of the target population, the study area presents low-density values and a relatively low percentage of young residents. Despite these values, there is some potential to promote cycling to achieve the goals of the National Strategy for Active Mobility (10%).

4.2. Assessing the Potential for Cycling—Target Area

The cycling conditions were assessed according to slopes, street hierarchy, geometry of the street network and proximity to community facilities.

Street slopes were evaluated by considering three classes (<3%, 3–5%, >5%). The evaluation shows that the overall topographic conditions are not very attractive for cycling (Figure 4A). In the study area, the elevation ranges from 5 m near the Lima River up to 100 m in the southern sector. According to the results, 25% of the street length is suitable for cycling (slopes <3%), but 41% has slopes between 3–5% (less suitable for cycling), while 34% has slopes >5% (not suitable). The most suitable streets are particularly found in the valley area, while the hilliest terrains are found in the historical center and in the southern sector of the study area, namely at some local distributor streets that connect the city center with the surrounding areas, such as the national road N203.

Regarding the street hierarchy, the study area includes main distributor, local distributor and local access streets (Figure 4B). According to the results, 57% of the street length comprises local access streets, e.g., streets characterized by low traffic speed and volume. These local access streets are mainly found in dense and compact urban areas, such as the city center and in residential and commercial areas widespread by the study area. The local distributors represent 25% of the street length and they mainly connect the main distributors with the local access streets. Finally, the main distributors correspond to 18%

of the street length. In the study area, these streets correspond to national roads, such as N201, N307 and N203 (Figure 4B).

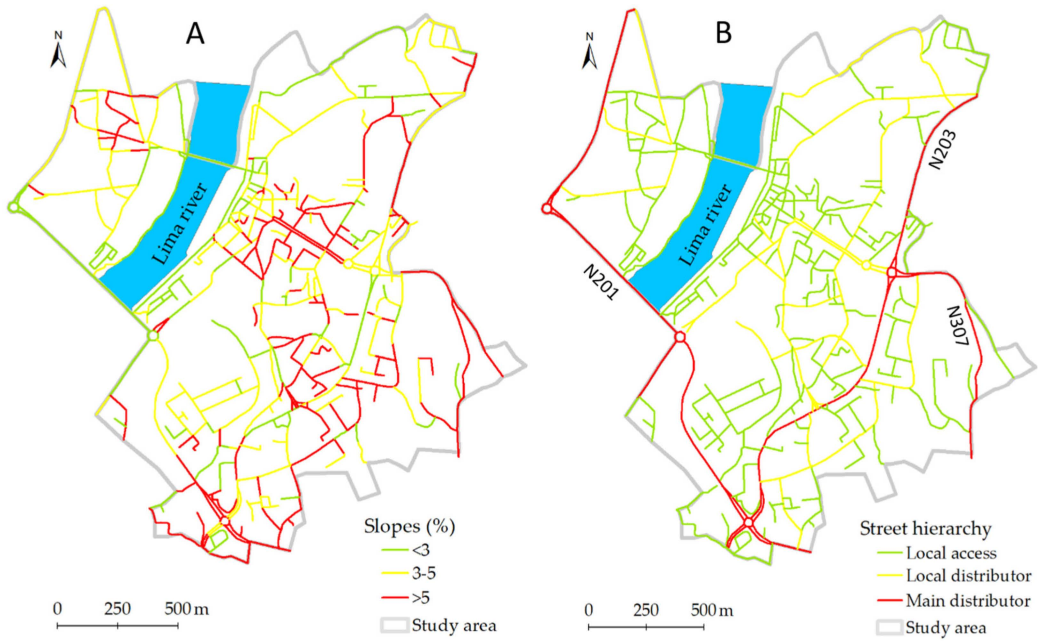

Figure 4. Street slopes (**A**) and street hierarchy (**B**) in the study area.

The geometry of the street network was analyzed through the Space Syntax measure of integration. The street analysis was first performed on DepthmapX and then the output was exported to GIS. The results are shown in Figure 5A. As explained in Section 3.2, high integration values are associated with fewer segments to pass through to reach a specific destination. According to the results, the level of integration ranges from 0.08 (lowest integrated segments) up to 0.31 (highest integrated segments). The streets with high levels of integration (>0.251) are located in the central area and include the historical center and the surrounding urban spaces. This includes local access and local distributor streets and segments of some main distributor streets. In turn, the streets with low levels of integration are found in the most peripheral spaces and more particularly in the north sector of the study area. These areas are not as topologically close as the remaining urban spaces and, therefore, are less connected to the remaining street network.

Regarding the proximity to community facilities, Figure 5B shows the distribution of the five selected facilities. The educational facilities are represented by one high school that has a central location in the study area, by one professional school and by one university. Three other facilities (hospital, town hall and police station) are located in the same area and in close proximity to each other (less than 300 m). Other public facilities (tax office, stadium, court) are also located in this place, making this area particularly diverse, functional and attractive. In terms of transport facilities, the bus station has a somewhat peripheral location near a main distributor (N203). Finally, three urban parks are found in the study area: two of them are near the Lima River, while the other has a more peripheral location near the professional school. To sum up, the selected community facilities are widespread in the study area and, except for the town hall, are all located outside the historical center. All community facilities are within the maximum recommended cycling distance (<5 km).

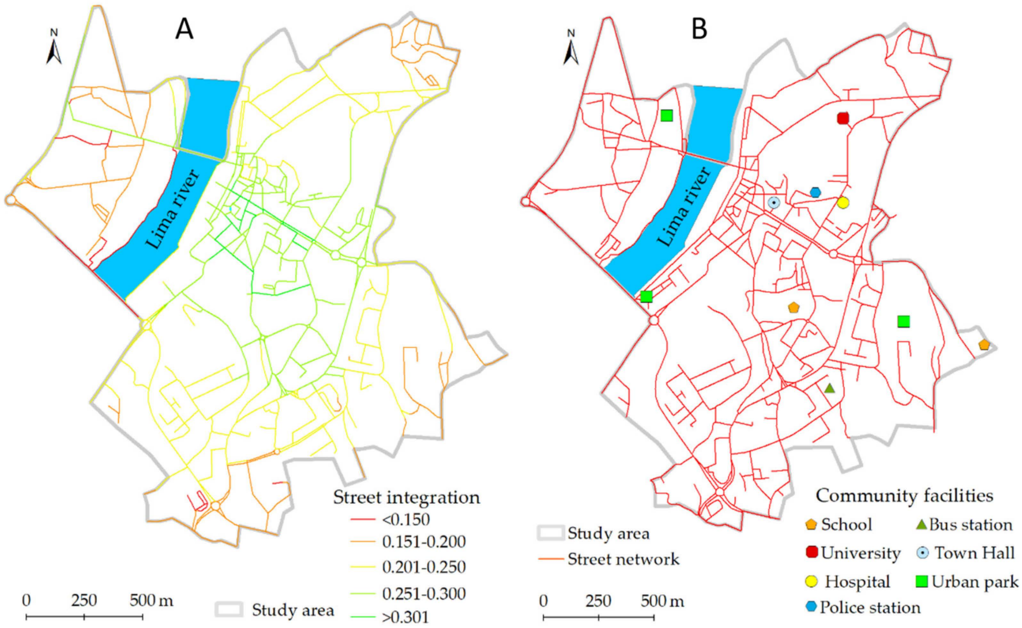

Figure 5. Street integration (**A**) and community facilities (**B**) in the study area.

4.3. Bicycle Network for Ponte de Lima

Considering the described target population and target area attributes, the potential cycling network is shown in Figure 6. The proposed network comprises three types of cycling infrastructure: segregated cycle lanes, colored cycle lanes and a set of streets where cycling will coexist with other road users (combined traffic).

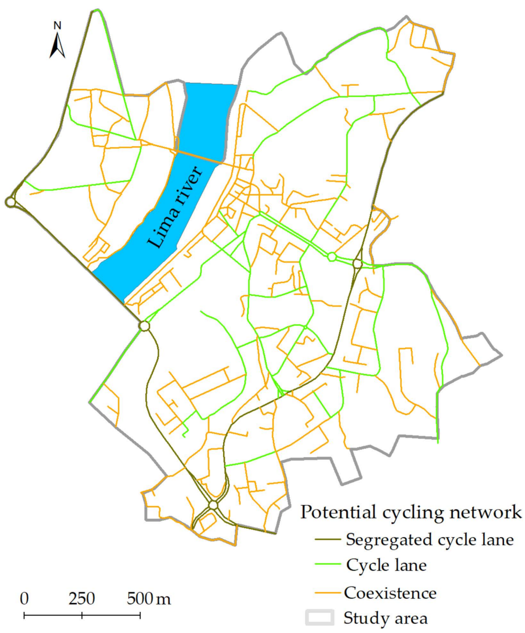

Figure 6. Potential cycling network for the study area.

Segregated cycle lanes correspond to separate lanes to be constructed along the main distributor arterials. These streets are the only ones with enough width (7 m) to allow the construction of a laterally separated cycle lane that should ideally be 1.2 to 1.5 m wide. An extension of the existing cycle lane to the other side of the Lima River is proposed so that these areas could have good bicycle access to the main urban center. The proposed cycle lane has a total extension of 6.5 km that crosses and borders the whole study area.

Although the main distributors are the streets with high traffic volume and speed, the segregation from motorized vehicles will enhance cyclists' safety and comfort. As found in the existing lanes, this can be undertaken by installing pillars every 2.5 m on the left-hand side of the separated bicycle lanes.

A network of colored lanes is proposed to mainly connect the segregated lanes with the streets in coexistence. The distinct coloration of cycle lanes in relation to traffic lanes and pedestrian areas provides a clear route, which makes cycling more attractive, legible and intuitive. Although these lanes do not provide a physical separation from motorized traffic, they increase the visibility of cyclists, namely in conflict areas, such as at intersections and roundabouts, which also helps to improve cyclists' safety. The proposed network of colored cycle lanes has an overall length of 12.4 km that mainly corresponds to local distributor streets with two lanes, being wide enough to install a cycle lane.

Finally, the lowest level of the hierarchy comprises a network of streets where bicycles and motor vehicles share the same space. These streets mainly consist of local access streets, e.g., narrow streets usually with one traffic lane found in denser and more compact urban spaces, such as in the city center. To ensure a safe coexistence between bicycles and vehicles, it is important to ensure a speed limit of 30 km/h and a relative homogeneity of the types of vehicles circulating on these streets. The total network length of streets in coexistence is 24.6 km.

5. Discussion

This paper aimed to present a planning practice method to assess the potential for cycling and design a bicycle network in Ponte de Lima, a Portuguese starter cycling city. The method included target population attributes related to population density and age, as well as target area attributes related to the road network and land use.

The analysis showed that Ponte de Lima is not very attractive for cycling due to the topographic conditions, but also because the city just provided a few sparse cycle lanes that are not part of a coherent network. The current bicycle facilities do not suit the basic cyclists' needs, namely those that may use or are likely to use bicycles for daily commuting purposes (going to work or to school). The overall cycling conditions provided by the city are poor, resulting in a very low bicycle modal share. As highlighted by Lopes et al. [17], when cycling infrastructure is incipient, selecting the basis for a future cycling network is of the utmost importance, as a low adherence in the early stages may discourage further investments in cycling infrastructure in the future. With this in mind, the planning approach described in this paper was designed to meet future cyclists' needs by providing appropriate facilities and an effective cycling network, which can be used to support future planning decisions and prioritize investments. It has the potential to help the city in reaching the goal of the National Strategy for Active Mobility (bicycle modal share of 10% by 2030).

The described planning approach is based on some principles, namely on the following assumption: (i) the road network is the basic facility available for cycling; (ii) key origins and destinations should be accessible and connected in an adequate and functional manner; (iii) bicycles should be integrated with other modes of transport; (iv) a bicycle infrastructure should be provided whenever possible; and (v) the characteristics of the population (potential users) should be taken into account. These principles were evaluated by specific attributes that helped in defining the extent to which the built environment provides safe, comfortable, attractive, cohesive and direct routes for cycling.

The proposed cycling network comprises segregated cycle lanes, colored cycle lanes and a set of streets where cycling will coexist with other road users. Creating a separate cycle lane aims at protecting cyclists from motorized traffic, which has a greater mass and circulates at higher speeds. Safety is a well-known barrier preventing people from cycling on a daily basis [13,68]. Considering this, we argued that the existing separated bicycle lanes should be extended to a broader area of the city (from 3.3 km to 6.5 km) and the intersections at roundabouts should be improved. Nonetheless, the proposed segregated lanes represent around 15% of the total street length in Ponte de Lima. A fully separated bicycle network from vehicular traffic will not be realistic due to the costs involved and to the compact and dense urban structure found particularly in the city center. As emphasized by Reggiani et al. [25], few cities around the world have a fully connected network of separated bicycle lanes. Bicycle networks often consist of a heterogeneous set of streets providing various safety and comfort levels for cyclists. In many streets of Ponte de Lima, the available street space is not enough for all road users' needs, which makes the creation of separate cycle lanes impractical.

At an intermediate level, we proposed the creation of a network of colored cycle lanes to connect the segregated lanes with the streets in coexistence. These facilities, which are missing in the current street network, aim at providing a segregated space for cyclists in streets where the lack of space makes the creation of separated lanes impossible. Colored lanes are known for bringing various benefits to cyclists. As shown by Autelitano and Giuliani [69], colored lanes enhance not only safety as drivers tend to slow down and avoid parking on these lanes, but also a clearly delineated route, making the cycling infrastructure more attractive, legible and cohesive. These colored lanes should be connected with the segregated lanes and complemented by a set of measures (such as reducing traffic speed) to enhance safety and comfort. By doing so, these colored lanes can act as "tactical urbanism" [69] as they can be used to guide future interventions in terms of rearranging urban streets and traffic.

The lowest level comprises the streets of coexistence, which mainly includes local access streets. According to the CROW manual [43], bicycles can share and coexist with motorized traffic when some traffic conditions (homogeneity of the types of vehicles and a speed limit of 30 km/h) are guaranteed. Evidence from bicycle-friendly countries also confirms that these streets are safe and attractive for cyclists when speed is limited to 30 km/h or less, and vehicles are forced to slow down due to various infrastructure modifications, such as speed humps and raised intersections [70]. Designing such an environment in Ponte de Lima requires creating a slow-speed and well-signalized environment, where bicycles, motorized vehicles and other road users can safely coexist.

The performance of some of the described attributes may prevent people from cycling. The hilly terrain of Ponte de Lima is undoubtedly a barrier to utilitarian bicycling. In terms of length, the analysis showed that 25% of the segregated cycle lanes, 40% of the cycle lanes and 34% of the streets in coexistence have slopes above 5%, which are not suitable for cycling. Although the impact of slopes can be mitigated by particular urban design solutions and by using electric bicycles [17], some authors argue that slopes over 5% could be tolerated over short distances up to 240 m [31]. Ponte de Lima has 12 street segments longer than 240 m with slopes above 5%, which, therefore, could be the most critical points for cycling (Figure 7). Some street segments are also poorly integrated into the street network and may involve cycling greater distances (detours) to reach specific destinations. This problem is particularly found in the north sector of the study area (Figure 7), due to its position on the other side of the river. In terms of street hierarchy, in addition to the need for signalizing, reducing traffic speeds and protecting cyclists, there are various large single-lane and multilane roundabouts that also represent critical points for cyclists (Figure 7). In the current situation, these roundabouts do not contain any design element for cycling and, therefore, they represent interruptions in the sparse existing lanes. It is important to create cycling infrastructure on these roundabouts to prioritize cyclists and increase their safety, by creating on-road bicycle lanes or off-road cycle paths around them, with contrasting-colored pavements to improve drivers' awareness of the possible presence of cyclists and to provide visual separation for cyclists from cars. Finally, due to the small size of Ponte de Lima, the selected community facilities are all within cycling distances below 5 km. In this case, distance is not a main obstacle for cycling. The provision of parking facilities and bicycle-sharing stations at some community facilities (bus station, schools and university) will be particularly important to encourage people and the youngest groups (students) to cycle.

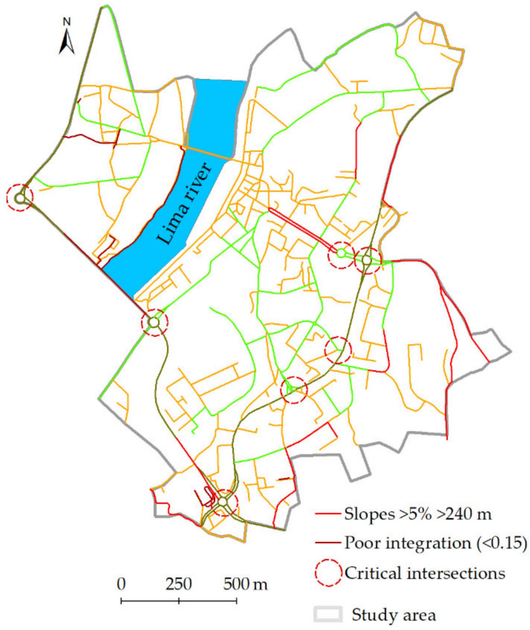

Figure 7. Critical points in the designed cycling network.

Regarding the target population, Ponte de Lima shows a relatively low potential for cycling. Age and population density are considered to have the highest influence on cycling potential [18], but Ponte de Lima has a low population density (18.8 inhabitants/ha) and a low percentage of the population aged 14–25 years old (18%). This could be explained by the small size and peripheral location of Ponte de Lima, which already contains many spaces classified as low-density areas in the national context. The number of potential users could also be increased by encouraging commuters (students, employed people) and visitors to use bicycles.

To encourage people to cycle, policies should focus on more than just physical infrastructure. As highlighted by Dias et al. [22], this can include, among other things, information, education and communication initiatives aimed at improving awareness of this transport mode and financial/economic incentives for cyclists. Education for mobility by bicycle has produced significant positive results in other cities [55]. Offering incentives (vouchers, financial rewards), for example, embedded in smartphone apps has proven to be effective in persuading people to cycle more often [71]. These policies could be complemented by measures aimed at restricting car use or parking. However, as highlighted by Dias et al. [22], these initiatives tend to be viewed as very unpopular, because in starter cities, the car plays an important role as a mode of transport and as a status symbol.

Finally, this study has three main limitations that should be mentioned. Firstly, to assess the potential for cycling and design a bicycle network in Ponte de Lima, we selected a set of attributes to fit five main dimensions (safety, comfort, directness, cohesion and attractiveness). However, the potential for cycling is influenced by many other individual, natural and built environment variables that were not included in this study. These include, for example, the willingness to replace cars with bicycles on daily trips, car ownership, weather conditions, type of pavement and traffic direction, among others. For example, in a study conducted in a city located in the north of Portugal, Ribeiro et al. [72] concluded that owning a car and the weather conditions during the winter were the two most important reasons preventing the use of active modes of transport. The type of pavement may also substantially affect the cyclists' comfort. In the city center, many streets are paved with cobblestones, which are known for producing vibration [56]. Secondly, the method for assessing the potential for cycling and designing a bicycle network in Ponte de Lima could be supported by a quantitative decision-making tool, such as a multicriteria analysis, through which the various attributes were weighted and scored according to, for instance, the opinion of a group of experts. This will result in ranking the streets according to their potential for cycling, which could be useful to prioritize policies and investments. Thirdly, the population living and commuting to Ponte de Lima and the municipal decision-makers were not directly involved in this study. It could be interesting to collect their opinions and suggestions to incorporate public participation in designing the bicycle network and to understand in depth their willingness to switch to bicycles.

Therefore, there is room for improvement in future studies. A valuable future contribution would be to track the adoption and the success of the described planning actions by measuring the growth in cycling share in Ponte de Lima. Approaching target stakeholders (planners and decision-makers) and surveying the population will be helpful for understanding and incorporating their points of view in bicycle planning practices. To obtain more robust cycling data and a dynamic overview of cycling, bicycles equipped with a GPS could be used for monitoring the usage levels and the specific paths chosen by cyclists between specific origins and destinations in the next stages of the work. We plan to study these issues in future work.

6. Conclusions

Considering the need to decarbonize the transport sector, cycling can be a feasible alternative to short car trips. In Portugal, cycling for commuting purposes is still very low: bicycle trips represented less than 1% of the modal share [21]. However, during the last decade, many cities have implemented policies and made investments to make this mode of transport more attractive, comfortable and safe. During the COVID-19 pandemic, the anxiety over public transport and the need to exercise prompted a significant increase in the number of cyclists. This was also the case in Portugal where the number of cyclists increased by 19% [73]. This boom may help to reach the goal defined by the National Strategy for Active Mobility of having bicycles represent 10% of the modal share by 2030. In addition to this rapid growth, most Portuguese cities are starter cycling cities [22], which are characterized by significant inertia in adopting bicycles and implementing effective planning policies. The prevalent mindset within Portuguese planning authorities is to assume that cities usually do not have the necessary features to foster a new cycling culture [17].

This is the case of Ponte de Lima, which has a residual bicycle modal share (0.3%) and where, only recently, some sparse and disconnected bicycle lanes were provided. In this paper, we described a planning practice method to assess the potential for cycling and design a bicycle network for this city. The planning method is guided by a systematic approach that comprises population (potential demand) and built environment attributes (potential supply) by using GIS and Space Syntax operations. This includes the population with more propensity to cycle, slopes, street hierarchy, geometry of the street network and proximity to community facilities. It was concluded that the low population density and percentage of young individuals living in Ponte de Lima are barriers to cycling. Attracting commuters and visitors to cycle could help in mitigating this problem. On the other hand, the city is compact and the main destinations are up to 3 km in distance, which makes the use of the bicycle convenient. The level of street integration enhances topological proximity, but slopes could be a barrier for cycling, namely in segments longer than 240 m with more than a 5% gradient. The proposal is to extend the existing segregated cycle lanes, provide a network of colored lanes and a network of streets in coexistence between cyclists and motorized traffic. As highlighted by Moura et al. [8], the purpose of a cycle network is to provide cyclists with safer and more convenient cycling mobility. The success of these planning guidelines will depend on adopting complementary measures, such as the improvement in the cycling conditions at complex intersections and roundabouts, adopting traffic calming policies, the provision of a bicycle-sharing service, education and communication campaigns, and incentives for cyclists, among others. Implementing these measures will not only provide the city with a bicycle network but also make cycling more appealing, safer and convenient. Thus, Ponte de Lima could be a representative case study for other small starter cities with similar problems and inspire adopting identical planning actions to facilitate the implementation of cycling as a daily mode of transport.

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