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The Potential Impact of Cycling on Urban Transport Energy and Modal Share: A GIS-Based Methodology

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Abstract: This article presents a methodology to estimate the maximum potential impact of a well-built and conserved cycling infrastructure, measured as modal share for accessibility trips, as well as the associated transport energy that can be saved in those trips. The methodology uses Geographic Information Systems (GIS) to estimate active trip probabilities, from which the output variables can be obtained. It was applied to a case study of a mid-sized city in Southern Europe, and results show that an adequate cycling infrastructure can achieve cycling mode share in that city on par with the world's most cycling-friendly cities. Concerning transport energy, a full-cycling scenario is estimated to reduce fossil energy intensity by approximately 20%, mainly by inducing a mode change for residents on the closest outskirts. It is also argued that cycling investment in commuting routes will have the most impact on reducing fossil transport energy.

Keywords: cycling; GIS; modal share; transport energy; urban planning

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1. Introduction

Rising concerns over traffic congestion in cities, greenhouse gas emissions (GHG), transport energy spending, and related health issues have led to a surge of interest in active mobility from academics, practitioners, and policymakers [1–10]. Cycling, in particular, has been a prominent research topic in both transport and spatial planning, with many studies highlighting its importance and benefits as a means of transport and commuting solution. Cycling is a promising mode of transport for urban mobility, ideal for trips up to 5 km [11,12], has low energy intensity and near-zero emissions, and thus has been increasingly recognized as a cleaner, healthier, and overall more sustainable mode of transportation [12–17]. Cycling is also an affordable, low-congestion, and readily available mobility option, which can cover large areas and daily movements when urban areas are dense enough [18]. Commuting by bicycle also has important indirect health benefits for surrounding inhabitants [19,20].

The benefits of cycling prompted major international authorities, such as the Organization for Economic Co-operation and Development (OECD), the European Commission (EC), and national and municipal authorities, to promote, invest in, and create the necessary infrastructure for it to become a viable daily means of transport [18,21–34]. Furthermore, the unexpected SARS-CoV-2 (COVID-19) pandemic has also played an important role in the last years, with climate-friendly transportation solutions that indirectly enforce social distancing starting to be seen as pandemic-resistant solutions as well [35–37]. This realization led to an even bigger push for cycling as a means of transport in urban areas, with cities such as London, Paris, Barcelona, Milan, Brussels, Bogotá, Berlin, Seoul, and Budapest promoting cycling and improving and creating infrastructure at a faster rate [38–41].

Nevertheless, cycling infrastructure needs to be properly implemented, as evidence has emerged that failure to meet cyclists' concerns highly deters people from choosing that transport mode [42]. Moreover, because the investment needed to promote, create, and adequately maintain cycling infrastructure is typically high, it is an arduous task to achieve, especially in consolidated cities which, over the last decades, prioritized motorized transportation. Therefore, to properly analyze the cost–benefit relation of cycling infrastructure investments, the need arises to estimate the maximum potential impact of those investments. This article proposes a methodology to provide an initial estimation of that impact, measured by modal share and transport energy use. It relies on evaluating active trip probability for accessibility trips to urban facilities and jobs, which constitute a high percentage of all urban trips [43] and uses Geographic Information Systems (GIS) to execute the city-scale calculations required.

The methodology allows for a comparison between a base scenario, where cycling is not considered as a feasible means of transport (i.e., it has near-zero modal share), and a scenario in which cycling infrastructure has been implemented in the best possible way, following all engineering codes of practice and along pleasant environments. Such implementation means segregation of the cycle mode from other modes (pedestrian and motorized), with cycle tracks of adequate lane width, quality and well-maintained pavement, cycle parking facilities, safety measures against motorized traffic, and placement of mechanical aid devices for the case of hilly cities. Codes of practice for cycle tracks can be found in [44] and placement of aid devices in [45]. For quality and maintenance issues (including safety), see, e.g., [46,47]. The methodology output gives municipal authorities valuable preliminary data to analyze the cost–benefit relationship of retrofitting their cities to include large-scale provisions for the cycling mode. The city of Coimbra, Portugal, a city with considerable urban sprawl and almost nonexistent cycling modal share, was used as a case study to demonstrate the concept. Results show that with adequate cycling infrastructure, Coimbra can aspire to have active modal shares on par with top-tier cities, such as Amsterdam or Copenhagen. To the best of the authors' knowledge, this is the first quantitative methodology to estimate the potential impact of a full-cycling scenario at various levels and one of the first case studies thereof.

Note that while an adequate cycling infrastructure removes the most important barriers to cycling (see, e.g., [48–50] for a list), promotional measures may be needed. These can be, for example, implementation of bike-sharing systems, institutional advertising, provisions for bicycle storage in public transport (multimodal approach), incentives to bicycle acquisition, or the creation of congestion taxes and restricted access areas. These factors may increase cycle mode share, but the study of their effect is beyond the scope of this article, which focuses on accessibility.

2. Literature Review

The large-scale impact of cycling on an urban area can be studied and evaluated in various ways. Modal share and transport energy spending are commonly used measures in transport planning as evaluators of mobility [51–54] and indicators of the impact of the creation or redevelopment of infrastructure [27,37,55,56]. Likewise, those indicators were used to evaluate the effects of new cycling-related policies or the reform of old ones [27,54,56–58], the implementation of various mobility-related services, e.g., bike-sharing [59–61], and combinations of policies and services [62,63]. Modal shift towards cycling has, in turn, socio-economic, travel behavior, and overall mobility impacts [64–66]. At a more general level, modal share and transport energy spending were also used as evaluators of the momentum towards renewable and non-polluting sources of energy [67–73].

The various studies mentioned above focused on the impact of one or two cycling-fostering policies or services, or infrastructural improvements of limited scope. None estimated the potential impact that a full-scale intervention on the cycling infrastructure could have, one which would leave citizens with no excuse *not* to opt for the cycling mode, except trip distance. It is to fill this literature gap that the present research is presented. The only study in the literature that is similar in objective to this article is that of Raustorp and Koglin [51]. However, those authors studied only commuting trips, at a different, regional level, and focused on health benefits. No trips to urban facilities were considered, and energy impacts were not estimated.

It is worth noting that during the COVID-19 pandemic, factors came into play which created fluctuations in cycle use [74]: lockdowns decreased overall ridership, but recreational/exercise trips increased. Cycling commuting trips also rose when economic activities resumed, feeding mostly from a modal shift of public transport users to cycling [75,76]. Being a low-contagion mode, the need to quickly create cycling infrastructure led to the appearance of dedicated planning tools [77] and the subsequent investments were made on the field infrastructure, which is likely to generate sustainable increases in the cycling modal share into the future [37,78], possibly to levels not expected so soon, had the pandemic not occurred. The present article presents a way to estimate what the maximum expectable share might be.

3. Materials and Methods

The methodology is based on the ideas below. These describe the procedure in broad brush strokes, after which finer details are given.

1. An urban area is selected for study. Three datasets are collected and curated into a GIS environment: origins (O), destinations (D), and road network. Origins represent demand (for trips) and are the centroids of residential buildings over the study area. Destinations represent supply and consist of urban facilities and centroids of job zones. The road network connects origins to destinations.
2. For each origin, network distances are evaluated in GIS to (*a*) the nearest urban facilities of each kind and (*b*) the centroid of each job zone.
3. The following transport modes are considered: walking, cycling, private motorized transportation, and public transport. For each OD pair, trip probabilities for all those modes are obtained. The cycling mode is, however, considered only in one scenario (see #4 below). If it is considered, the trip probability for walking and cycling modes is evaluated as a function of distance and combined into a single active modal probability.
4. Two scenarios are evaluated: a first scenario, where cycling is not considered as a means of transport (i.e., cycling modal share set to 0%; only three transport modes are considered), and a second scenario, where cycling is included. Modal share distribution and the associated transport energy spending are calculated for each scenario.

The four transport modes indicated above are comprehensive categories. This division has been considered in recent urban mobility analyses [79–82] and simulations [83]. The cycling mode includes any type of cycle, including pedelec cycles. However, for simplicity, this research considered only the most common type, the bicycle. Private motorized transportation refers to private vehicles which do not require human muscular energy for locomotion, such as cars, motorcycles, scooters, etc. Public transport refers to any form of public transportation. Again, for simplicity, this research considered only the car for private motorized transportation and assumes this has an internal combustion engine (ICE). Likewise, for public transport, only ICE busses were considered.

The trips considered in the methodology are accessibility-related, with accessibility defined in the classic sense of the ease to reach destinations, i.e., interaction opportunities. Accessibility trips constitute the majority of trips in the urban environment and can be modeled in GIS as one-way or round trips to predefined destinations, subject to supply attractiveness and demand intensity.

The subsections below present implementation details and their rationale. Some GIS details are presented using the ArcGIS 10.8 tools language, but any other GIS environment can be used, provided its toolset can execute the operations described herein.

3.1. Defining the Datasets

As to what concerns dataset definition and curation, the methodological approach follows previously validated work by Monteiro et al. [83].

3.1.1. Origins

Centroids of residential buildings are given population information in their associated table. For large study areas, where route computational times might be too large, the alternative is to create a square mesh over the study area. The mesh size is tuneable, usually between 25 × 25 m and 100 × 100 m (smaller sizes yield greater precision but lead to longer computational times). Implementation involves creating the mesh and their centroids feature classes and then erasing centroids which lie a certain distance away from the road network, e.g., 50 to 100 m, together with their associated square polygons. Each mesh centroid is then given population information in its associated table using GIS *Join* tools. Finally, mesh squares and mesh centroids with zero population are erased.

3.1.2. Destinations: Urban Facilities

Destinations of the urban facility type consist of point feature classes. Facilities are divided into types, according to Table 1 below, and a feature class is created for each type. The points represent either building centroids or main entries. Destination attractiveness or weight needs to be considered when studying accessibility [84,85], and facility weights depend on their type. Following Monteiro et al. [83], this research proposes an empirical 1-2-3 Likert scale for weights, based on trip frequency, where 3 denotes the most frequent. Higher weights mean trips to the corresponding destinations are likely to be more frequent. For urban facilities, the above weights are consistent with the trip frequencies per facility type found by Gov.UK [43]. Some trips to facilities are naturally two-way trips, i.e., round trips, where the person returns to the origin soon after reaching the destination (e.g., supermarkets or post offices), while others are one-way, implying a long stay at the destination (e.g., entertainment). Because of the feeling of a longer distance when permanence time at a destination is short, distance to facilities which are likely to generate two-way trips is doubled in active trip probability calculations. Another point is that multiple opportunities should be considered in accessibility [86], as a person usually wants to have the option to reach, for example, several nearby restaurants or shopping centers. However, for some facility types, the person usually goes to the closest one, e.g., pharmacies or post offices. Consequently, multiple facilities need to be considered only for facility types for which freedom of choice is relevant. As an example, Martínez and Viegas [87] considered freedom of choice to the five closest facilities, as well as facilities without such freedom. Table 1 below shows the facility types considered in this research and summarizes the above considerations. In the Case Study section a map is shown with the spatial distribution of those facilities over the study area.

Table 1. Facility types and jobs weights.

Weight 1 Facilities	Weight 2 Facilities	Weight 3 Facilities
Post offices *,2	High schools 1	Kindergartens *,2
Sports facilities 2	Shopping centers 2	Primary schools *,2
Cultural organizations 1	Entertainment sites 1	Middle schools *,1
Universities and institutes 1	Primary healthcare services *,1	Grocery stores 2
Elderly care centers 1	Pharmacies *,2	Supermarkets 2
Churches 1	Restaurants 1	Bakeries and pastry shops 2
	Parks and green areas *,1	

* Closest only, 1 One-way facility, 2 Two-way facility.

3.1.3. Destinations: Jobs

Destinations of the job type require a different approach; as a person usually has only one job, the concept of “nearest job” does not apply. In addition, precise job destination figures require knowing where the people from each origin work, which, in turn, requires large scale surveys, which are, in general, unavailable. Thus, this research uses traffic zone analysis [88,89] to approach job accessibility. This is implemented as follows [83]: identify job locations and employee count; assign these to a 'jobs' point feature class; divide the city into zones and create a 'job zones' polygon feature class; count jobs in each zone (intersect 'jobs' and 'job zones'); and find the geometric average job location of each zone (GIS *Mean Center* spatial statistics tool). Finally, for each origin, calculate the distance to each job zone geometric average. Jobs are considered one-way facilities and their weight is proportional to the percentage of commuting trips within the study area. All job zones centroids are considered as destinations, and a ponderation by the fraction of jobs in each zone is later applied (see Section 3.4 below for details).

3.1.4. Road Network

The road network is the one existing on the field, with the addition of walking and cycling dedicated infrastructure, where it exists. Because of dedicated infrastructure, distance to facilities may depend on the transport mode, although the differences are usually small.

3.2. Obtaining GIS Distances

For deriving distances to facilities, the ArcGIS *Closest Facility* tool is used. The maximum snapping distance, i.e., straight-line distance from the network to a destination (or origin) point is the same used to remove faraway origins (usually 50–100 m). If a destination lies inside the study area but sits more than the snapping distance away from the network, then the snapping distance can be increased for that facility type. Motorized, walk, and cycle OD distances are obtained by solving *Closest Facility* problems for each facility type and transport mode. For facilities where freedom of choice is relevant, the distance to the K-closest facilities is calculated. For other facilities and jobs, K is always 1. For two-way facilities, OD distances are multiplied by two (if many one-way streets exist, separate towards and away distances can be calculated separately and added). All the OD distances obtained are stored in the origins feature class associated tables.

3.3. Estimating Modal Split

3.3.1. Individual Walking and Cycling Trip Probabilities

On the basis of the OD distance, a probability for carrying out the trip in active mode (walking or cycling) is calculated as follows. First, trip probability for individual walking and cycling modes is modelled via a log-logistic distribution:

$$p(x) = \frac{1}{1 + \exp(a + b \ln x)} \tag{1}$$

where a and b are parameters, and x the network distance for the respective travel mode. The log-logistic function was chosen because it provides a good fit to experimental data, as recognized by Hilbers and Verroen [90] and Geurs and van Wee [86], and is not sensitive to small x instabilities that other trip probability models exhibit. However, log-logistic parameters for the walk and cycle modes are, in general, not available so for this research, they were obtained indirectly from the results of Yang and Diez-Roux [91] for the walk mode. Those authors presented walking trip frequency as a function of distance and trip purpose using a negative exponential law. Evaluating the distances for which the Yang and Diez-Roux law yields 10% and 90% walk probabilities, equating these benchmarks to Equation (1), and solving for a and b allows the log-logistic to be calibrated for the walk mode and for each destination type. This yields the parameters shown in Table 2 below:

Table 2. Log-logistic parameters for walking.

Destination Type	a_j (Distance: Km)	b_j (Distance: Km)
Post offices	1.19225	1.83021
Sports facilities	0.05574	1.83013
Cultural organizations	1.00344	1.82990
Universities and institutes	1.07775	1.82989
Elderly care centers	1.19225	1.83021
Churches	1.00344	1.82990
High schools	1.07775	1.82989
Shopping centers	1.19225	1.83021
Entertainment sites	1.00344	1.82990
Primary healthcare services	1.19225	1.83021
Pharmacies	1.19225	1.83021
Restaurants	1.46215	1.83009
Parks and green areas	1.00344	1.82990
Kindergartens	1.46215	1.83009
Primary schools	1.46215	1.83009
Middle schools	1.46215	1.83009
Grocery stores	1.19225	1.83021
Supermarkets	1.19225	1.83021
Bakeries and pastry shops	1.46215	1.83009
Jobs	0.89627	1.83017

For the cycling mode, users typically spend a similar time buffer in cycling trips as in walking trips [82]. However, the distance ridden by a bicycle is greater due to its higher speed. Walking speed can be modelled by, for example, Tobler's hiking function [92], and cycling speed is available from Parkin and Rotheram [93]. Similar speeds, albeit slightly smaller, were found [94–96]. For zero slope, the Tobler walking speed is 1.4 m/s, whereas cyclist speed sits at approximately 6.0 m/s. The ratio of the two is approximately 0.233, which can be used as a multiplier for x for cycling trips while keeping the same a and b values of Table 2. A very similar ratio of walk/bike average distance was also found by Ton et al. [82].

3.3.2. Individual Walking and Cycling Trip Probabilities

The second step in obtaining an active trip probability requires combining walking and cycling probabilities into one single probability. This can be accomplished considering two *ansätze*: #1 for short distances, one has the choice either to walk or to use a bicycle. Thus, the probability p_A of making the trip using an active mode can be modelled by the probability of walking (p_W) or cycling (p_C) to the destination. Mathematically, this can be expressed by $p_A = 1 - (1 - p_W)(1 - p_C)$, where p_W and p_C are obtained by applying Equation (1) for distances x and $0.233x$, respectively. The above reasoning can be extended to all x, but active trip probabilities modelled by distance–decay functions can be optimistic at large x, and, therefore, p_A above could lead to even more optimistic probabilities, possibly excessive, unrealistic ones (see [82,97] for examples regarding long distances lead to no use of active modes). For this reason, *Ansatz* #2 comes into play; for long enough distances, it is assumed that all active mode trips are of the cycling type. Defining what constitutes short and long distances is subject to decision-maker judgment; in this research, the following guideline is proposed: short trips are those for which $p_W \geq 0.50$, and long trips have $p_W \leq 0.10$. Trips in between are modelled by a linear interpolation between the two *ansätze*. The mathematical expression for the unified active trip probability is then:

$$p_A(x) = \begin{cases} 1 - (1 - p_W)(1 - p_C) & p_W \geq 0.50 \\ p_C + \frac{1-(1-p_W)(1-p_C)-p_C}{0.5-0.1}(p_W - 0,1) & 0.10 \leq p_W \leq 0.50 \\ p_C & p_W \leq 0.10 \end{cases} \quad (2)$$

Recall that p_W and p_C depend on destination type j, so the active trip probability may read $p_{Aj}(x)$ to reflect this dependence. Equation (2) can be implemented in ArcGIS using the *Field Calculator* tool. Figure 1 below shows a graphical depiction of the trip probability curve for post-office access as a function of distance, x. In it, the p_W (blue) and p_C (red) curves are shown, along with the curve for walking or cycling following *Ansatz* #1 (dashed gray). The green curve is the interpolation result, Equation (2). The intersection of gray lines with the walking curve indicates the distances for which the walk probability is 50 and 10%.

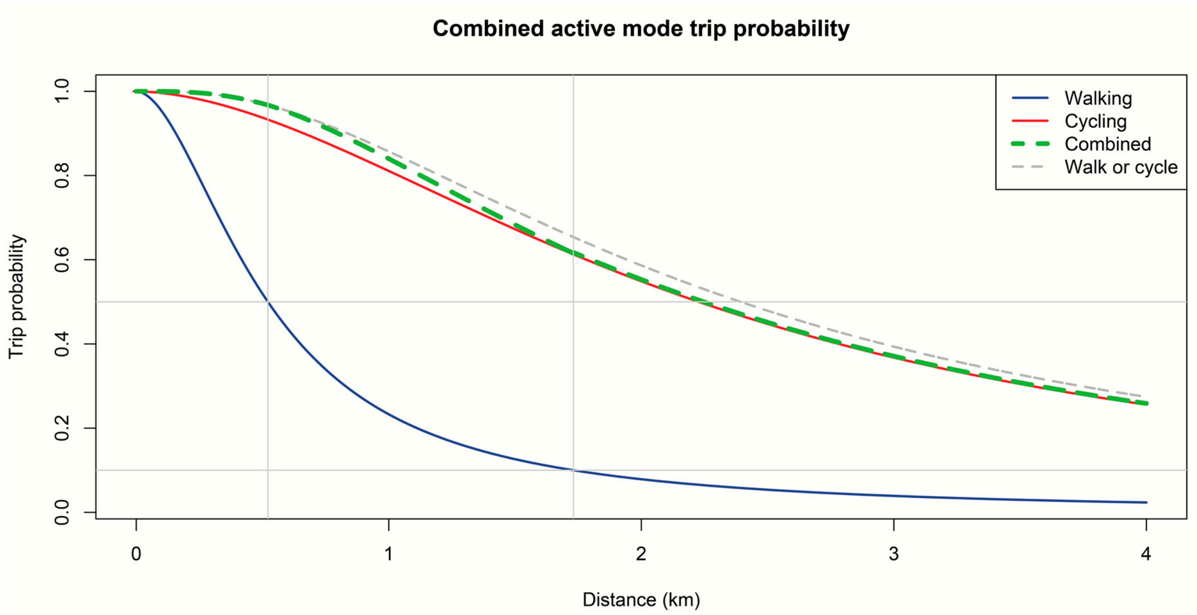

Figure 1. Combined active mode trip probability function for accessibility to post-offices.

3.3.3. Motorized Modal Split

Whenever a trip is not carried out actively, the person is assumed to resort to a motorized mode, which has consequences in terms of fossil energy spending and GHG emissions. The remaining probability is split between the private car and public transport (this split is equal for both scenarios). This research proposes a split based on the actual modal share for the study area, but other estimations of the modal split can be applied. Once the split is defined, fossil energy spending is evaluated. Walking and cycling are considered to spend zero fossil energy, and for private car and public motorized transport, average values per person can be assumed. In evaluating fossil energy spending, motorized trips are all two-way, as they in reality are.

3.4. Scenario Evaluation

Two indicators are obtained for comparing the no-cycling and full-cycling scenarios, namely active mode share and fossil energy spending.

3.4.1. Active Modal Share to All Destinations

The first indicator, active modal share, is obtained for every origin i by weighting active trip probabilities from that origin to all destinations by frequency and facility choice. This is accomplished using:

$$M_i = \frac{\sum_{jk} w_j L_{kj} p_{Aijk}}{\sum_j w_j \sum_k L_{kj}} \quad (3)$$

where

M_i: active modal share of origin i;
i: $1, \ldots, I$ number of origins;

j: $1, \ldots, J$ number of types of destinations;
k: $1, \ldots, K$ number of closest destinations of each type;
$p_{\mathrm{A}ijk}$: active trip probability from origin i to the k-th closest destination of type j;
w_j: attractiveness weight of destination of type j;
L_{kj}: choice factor for the k-th closest destination of type j; $L_{kj} > L_{k+1,j}$.

The $p_{\mathrm{A}ijk}$ are obtained by applying Equation (2) for facility type j. Note that facilities of the "closest only" type have $L_{kj} = 0$ for $k > 1$. The normalization factors in the denominator ensure that M_i values sit between 0 and 1 and can be interpreted as the doubly weighted average probabilities of performing accessibility trips with an active mode. The M_i values can then be displayed on a map.

For jobs, $p_{\mathrm{A}ijk}$ is obtained by a weighted-sum procedure over all job zones:

$$p_{\mathrm{A}ijk} = \sum_z f_z p_{\mathrm{A}iz}, \quad j : \text{jobs} \tag{4}$$

where

z : $1, \ldots, Z$ number of job zones;
f_z: fraction of total jobs in zone z;
$p_{\mathrm{A}iz}$: active trip probability from origin i to the z-th job zone centroid.

As for $p_{\mathrm{A}ijk}$, the $p_{\mathrm{A}iz}$ are obtained by applying Equation (2).

3.4.2. Fossil Energy Spending

Equation (5) is used to estimate the fossil energy spending associated to origin i:

$$E_i = \frac{\sum_{jk} w_j L_{kj} \left(1 - p_{\mathrm{A}ijk}\right) \left(p_{\mathrm{car}} F_{\mathrm{car}} + p_{\mathrm{pub}} F_{\mathrm{pub}}\right) \left(d_{ijk}^{\rightarrow} + d_{ijk}^{\leftarrow}\right)}{\sum_j w_j \sum_k L_{kj}} \tag{5}$$

where

p_{car}: fraction of motorized trips made using a private car;
p_{pub}: fraction of motorized trips made using public transportation;
F_{car}: private car average fuel economy (MJ/passenger.km);
F_{pub}: public transportation average fuel economy (MJ/passenger.km);
$d_{ijk}^{\rightarrow}, d_{ijk}^{\leftarrow}$: one-way distances from origin i towards/away, respectively, the k-th closest destination of type j.

The value $1 - p_{\mathrm{A}ijk}$ represents the left-over probability that an accessibility trip is carried out by motorized modes, which is then split into private and public transport. The normalization denominator results in Equation (5) the interpretation of the (again, doubly weighted) average fuel spending in accessibility trips, as measured in MJ/passenger-trip. As with M_i, the E_i values can be displayed on a map.

3.4.3. No-Cycling vs. Full-Cycling Scenarios

Equations (3) and (5) represent the full-cycling scenario. For the no-cycling scenario, it is sufficient to replace $p_{\mathrm{A}ijk}$ by $p_{\mathrm{W}ijk}$, the latter representing walk probability from origin i to the k-th closest destination of type j, a quantity that is directly available in GIS from intermediate steps (likewise, $p_{\mathrm{A}iz}$ is replaced by $p_{\mathrm{W}iz}$). Equations (3) and (5) and their no-cycling counterparts can be implemented in the ArcGIS environment using *Field Calculator*, and the results are stored in the origins feature class associated table.

4. Case Study

The methodology was applied to the city of Coimbra, Portugal, a mid-size city with approximately 104,000 inhabitants [98]. Data from Metro Mondego [99] disclose that the active modal share is approximately 22%, of which an abysmal 0.2% is cycling. The empirical motorized share splits as $p_{\mathrm{car}} = 0.7$ and $p_{\mathrm{pub}} = 0.3$, and the share of commuting trips is 37% (survey data), leading to $w_j = 22,\ j$: jobs. Concerning fuel economy, IEA [100] averages were used, namely 1.8 MJ/passenger.km for private cars and 0.7 MJ/passenger.km for public transport. For non-closest facilities, a choice parameter of $K = 3$ was considered, and two sets of L_{kj} were used for sensitivity analysis, namely $L_{kj} = \{70, 20, 10\}$ and $L_{kj} = \{50, 35, 15\}$. Results concerning the latter are presented in the supplemental material.

For generating datasets, building centroids could be used as origins, so there was no need to create a mesh feature class. The official Portuguese GIS databases were used to distribute the population by the buildings. The location and type of urban facilities in Coimbra were obtained from existing datasets, as well as job locations and employee count. Job zones were manually drawn in GIS, considering population density, buildings, job density, and orography. The detailed road network of Coimbra was obtained from OpenStreetMap. Figure 2a depicts the mesh centroids after empty and faraway polygon removal, facility locations, and road network. Figure 2b depicts job zones and their geometric average job locations, as well as specific job locations with over 100 employees. All maps were derived in the ArcGIS environment, with background imagery provided by that platform (*World Map Layer*).

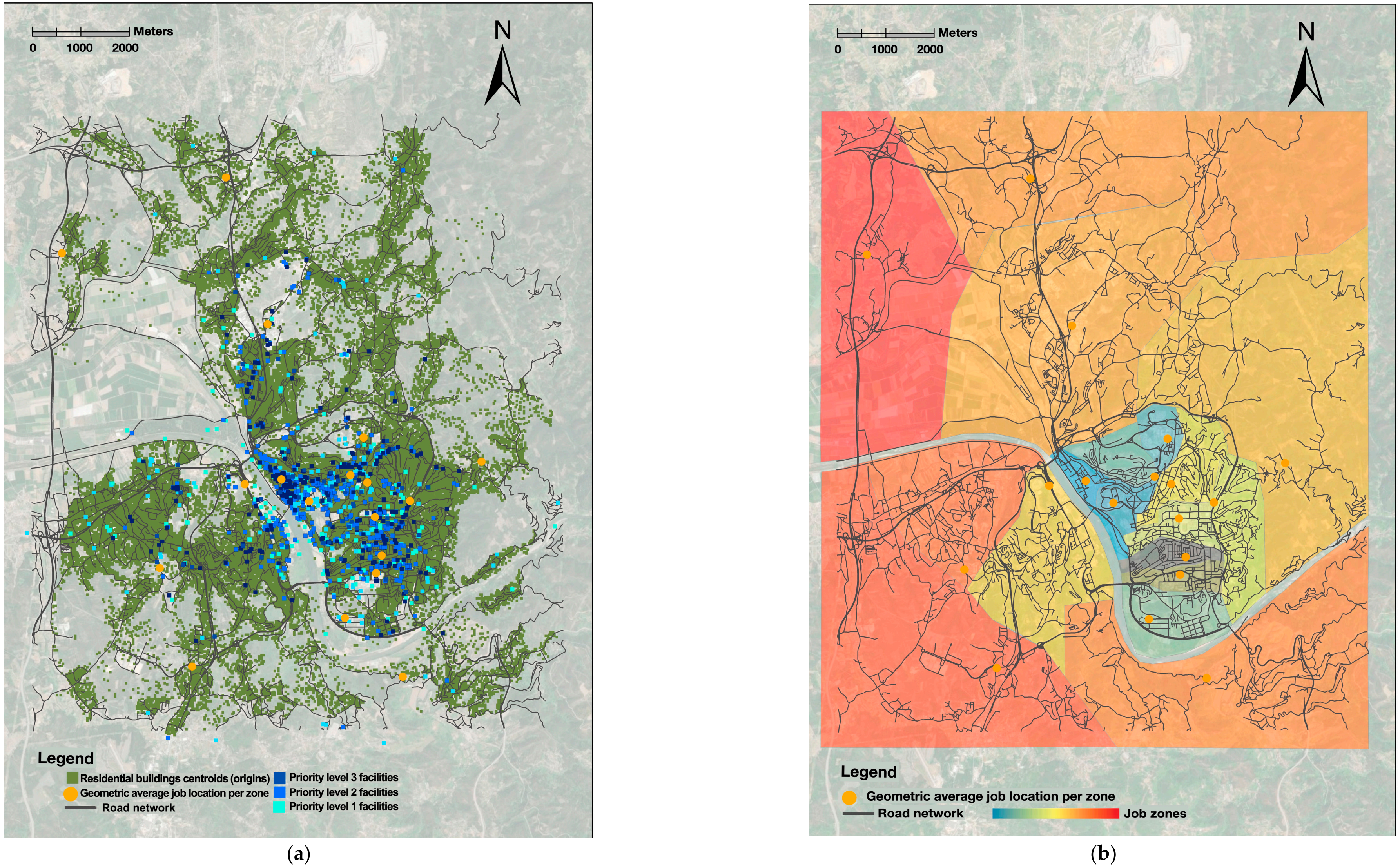

Figure 2. (**a**) Coimbra origins, urban facilities, and road network; (**b**) Coimbra job zones and main job locations.

5. Results and Discussion

Applying the methodology to the case study data yielded the results of Tables 3 and 4 and Figures 3 and 4. In Tables 3 and 4, the statistical calculations were carried out over mesh centroid data, except for the Average per inhabitant row whose statistics are related to centroid population, h_i, via the formulas $\frac{\sum_i M_i h_i}{\sum_i h_i}$ and $\frac{\sum_i E_i h_i}{\sum_i h_i}$ and are the main result of this article. The outcome shows that realizing the full cycling potential of Coimbra has a large impact on the cycling share for accessibility trips, more than doubling it, both for facilities and facilities plus jobs, putting it at the level of the world's most cycling-friendly cities, such as Amsterdam (61% active share) or Copenhagen (47% active share) [80,81]. Interestingly, the model–theoretical walking share for no cycling is 16.8%, which sits below the observed 22% [99]. This may be due to Coimbra having higher education as one of its main economic activities, which attracts many young people who typically resort to walking more often than older people. It may also be related to the effects of chained trips, i.e., trips to multiple destinations, and trips not related to accessibility, which were included in the survey [99] but which the present research could not consider.

Table 3. Active modal share summarizing statistics.

Active Modal Share Per Inhabitant (%)		Urban Facilities		Urban Facilities and Jobs	
L_{kj}	Measure	full cycling	no cycling	full cycling	no cycling
70/20/10	Min	3.3	0.5	3.5	0.4
	Max	94.3	71.8	73.7	48.0
	Average	45.8	18.6	35.6	12.7
	Average per inhabitant	55.3	24.7	42.6	16.8
	Standard deviation	24.9	15.9	18.7	10.6
	Coefficient of variation	54%	90%	52%	87%

With respect to energy spending, the impact of full cycling is a reduction of approximately 23% for accessibility to urban facilities and of 18% for facilities plus jobs. This impact is not as high as that for the modal share because Coimbra has a high urban sprawl. Fossil energy spending comes mostly from long-distance trips and faraway inhabitants, which are the biggest contributors to this spending, and have little chance to exercise a modal shift towards cycling. On the other hand, inhabitants near the center have better conditions for a shift towards cycling, but those inhabitants were already meager fossil fuel spenders. That full cycling has a high potential for modal shift but a lesser one for energy spending can also be seen from Figures 2 and 3, which graphically exhibit a larger discrepancy for the former. The differential maps of the supplemental material (Figure S7a,b) add visual insights: the modal share differential map shows that the most potential for a change towards active travel lies in the central regions, up to 2–3 km away from the city center, whereas for transport energy, the most savings appear in a ring-like area around that center.

Table 4. Fossil energy spending summarizing statistics.

Active Modal Share Per Inhabitant (%)		Urban Facilities		Urban Facilities and Jobs	
L_{kj}	Measure	full cycling	no cycling	full cycling	no cycling
70/20/10	Min	0.19	0.69	3.29	5.32
	Max	35.37	36.34	46.16	47.59
	Average	6.70	8.18	13.54	15.88
	Average per inhabitant	4.53	5.90	10.69	13.01
	Standard deviation	6.17	6.21	7.97	7.69
	Coefficient of variation	92%	76%	59%	48%

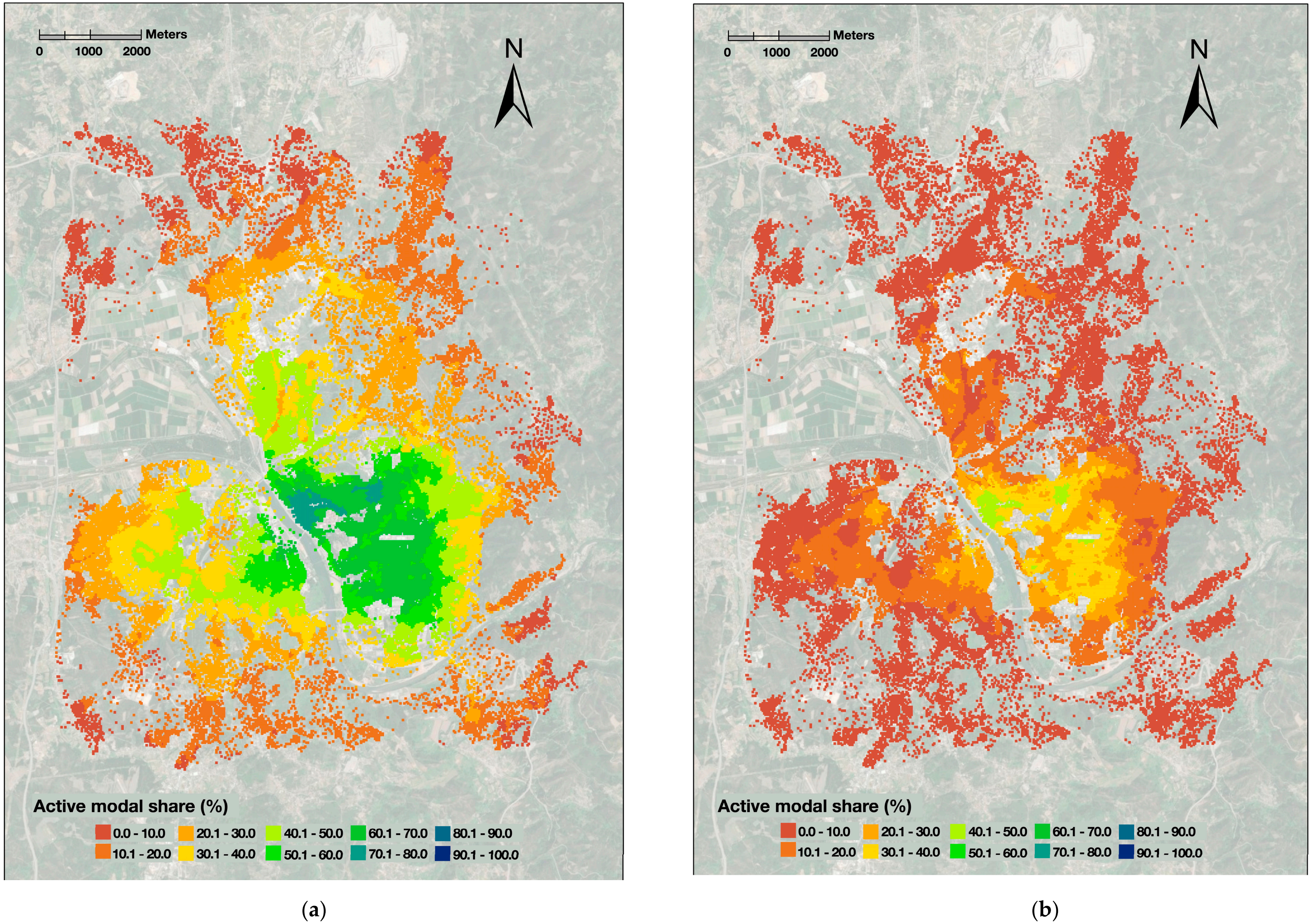

Figure 3. (**a**) Active modal share for full cycling: facilities and jobs; (**b**) Active modal share for no cycling: facilities and jobs.

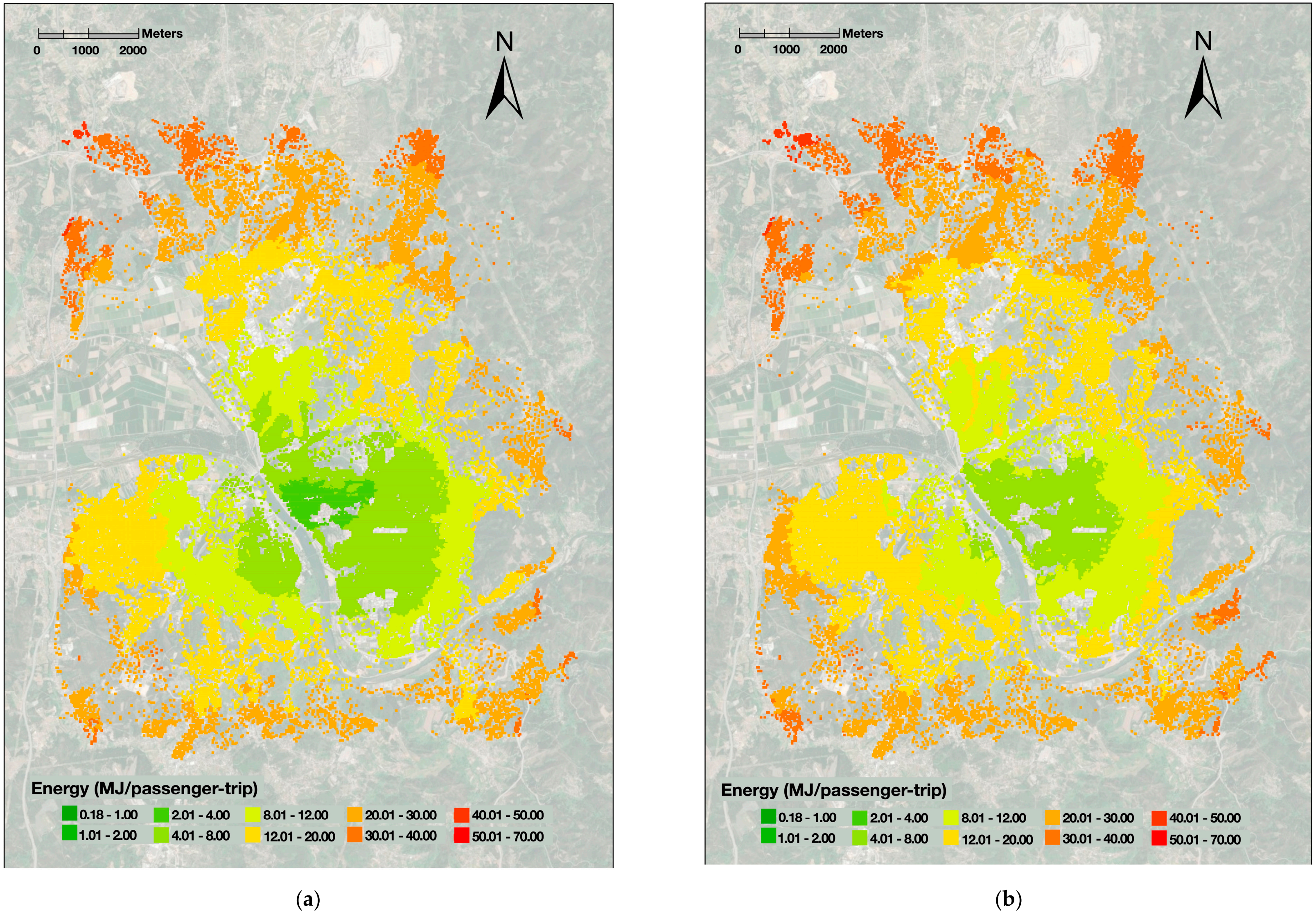

Figure 4. (**a**) Fossil energy spending for full cycling: facilities and jobs; (**b**) Fossil energy spending for no cycling: facilities and jobs.

Referring back to Table 4, for transport energy spending, the full/no cycling differential is larger for facilities plus jobs (2.32 MJ/passenger-trip) than for facilities only (1.37 MJ/passenger-trip), revealing that a significant portion of fossil energy spending comes from trips to jobs. This is due to longer average distances to jobs and their high daily frequency and is confirmed by Table S3 of the supplemental material, which shows a differential of 4.22 MJ/passenger-trip if job-only trips are considered. Such importance of commuting trips suggests municipal authorities should first concentrate financial efforts in constructing good commuting routes which can foster bicycle use for this type of destination.

Another noticeable insight from Tables 3 and 4 is that the full cycling scenario has lower dispersion measures, thus reducing the differences between those who live close to most facilities and jobs and those who live far away from those opportunities. This suggests cycling has a positive impact on equity in urban areas.

Despite the positive impact that cycling can have on both active modal share and transport energy spending, results show that urban sprawl still has a large impact, in line with similar results in the literature [101]. While cycling is known to be competitive compared with the private car in terms of time up to 5 km [11], this sprawling distance is inferior to that of the faraway regions of Coimbra, reducing the cycling potential for inhabitants of the outskirts and pushing them to the motorized modes. For these inhabitants, a way to reduce energy spending could be to promote a multimodal approach, e.g., transport of cycles on public transport, cyclists switching to busses when near the center.

A sensitivity analysis with $L_{kj} = \{50, 35, 15\}$ for non-closest only facilities was also carried out, statistical results being presented in the supplemental material. As per Equations (3) and (5), modal share and transport energy spending indicators degrade as L_{1j} decreases, but other than that, results do not significantly deviate from those of Tables 3 and 4; hence, no additional maps were generated.

Impact on City Planning

The above discussion leads to some conclusions with respect to city planning for the cycling mode. First and foremost, it was seen that even relatively sprawled urban environments (as Coimbra is) can aspire to high active modal shares, comparable to the world's top cycling-friendly cities. However, achieving a full cycling scenario is not an easy task [102], as there are several strong deterrents to cycling that need to be addressed, with safety from motorized traffic and hilliness as the top concerns [103–108]. Hilliness is a topographical limitation and cannot be easily overcome, but mitigation measures exist, such as the placement of mechanical assistance devices in critical locations [109] or electrical assistance of the cycles themselves (pedelec cycles). Safety from traffic can be achieved with the construction of dedicated cycling infrastructure or adequate retrofitting of existing roads. Indeed, the correct implementation of a cycling network will greatly mitigate safety concerns. However, due to the financial costs of such endeavors, it is not realistic to expect a quick change from the no-cycling scenario to the full-cycling one. This is where the evidence gathered in this research becomes relevant, as the expected fossil energy savings suggest that authorities should prioritize a cycling network for commuting routes. Several proposals exist in the literature regarding how to obtain the best routes [110–114], which can be implemented by municipal decision-makers.

Another conclusion is that urban sprawl considerably limits the potential energy savings of a full-cycling scenario. This suggests that compactification of urban space is a possible way to reach that scenario, or at least come closer to it. Compactification can be achieved in practice, for example, by urbanizing unused space within cities or regenerating derelict zones. Such actions typically appeal to the private sector, which sees to their execution. If conducted in a cycling-friendly way, compactification increases cycling network connectivity and directness, which was recognized by Dingil et al. [115] as a factor which may persuade users to shift to this mode.

It should be noted that constructing or retrofitting complete walking and cycling networks, following all engineering, safety, and level of service requirements, is typically very expensive and requires many years of execution. To maximize the return on investment, municipalities will want to prioritize certain routes, especially cycling ones, as these are more expensive to implement. Recent research on route selection includes [116], which proposed an infrastructure building information model (I-BIM) for cycle path design, and [117], where a cycling traffic model was presented, aiming at sustainable urban mobility planning. This model was applied to a case study where optimal improvement locations were identified.

6. Summary and Future Work

In this article, a methodology to evaluate the potential impact of cycling on cities on the basis of active trip probability to urban facilities and jobs is presented. This impact is measured by comparing active modal share and fossil energy spending in two scenarios; one where urban areas have yet not adopted cycling and another where cycling is a well-established means of transport. However, providing cycling with all the prerequisite conditions requires a collective effort from municipal authorities, from creating the adequate infrastructure for cycling to promoting cycling as an alternative. The methodology outputs are important preliminary data to evaluate the cost–benefit relationship of undergoing such constructive and financial efforts.

The methodology was applied to the city of Coimbra, a mid-sized city exhibiting considerable sprawl, that has an almost nonexistent cycling modal share. Results showed the distanced-based potential of cycling in Coimbra, with the full-cycling scenario having an expected increase of active modal share between 25.8 and 30.6% and a reduction of transport energy spending between 1.37 and 2.32 MJ/passenger-trip. These provide clear evidence of the impact that cycling can have on urban areas, creating better mobility conditions, less automotive traffic, improved health conditions, and overall higher sustainability. A finer-grained analysis revealed interesting planning insights, such as the recommendation to prioritize commuting routes or compactification of the city (if/where possible). Although the latter conclusions are based on the case study alone, the authors expect them to be general enough to constitute planning guidelines in their own right. The model has the limitation that it considers only accessibility-related trips. However, since these constitute a very significant fraction of urban trips, the results should not differ considerably from reality (i.e., all trips).

Applying the methodology to other cities or urban neighborhoods and comparing results with Coimbra is a natural first step for future work. Other extensions of this work include analyzing the effect of chained trips on the results, whereby multiple destinations on each *sortie* are considered (e.g., home–work–shop–home), evaluating how effectively hilliness can be mitigated by pedelec cycles or mechanical aid devices, investigating the effects of weather on the results [118], or considering a multimodal approach (e.g., cycling plus public transport). On the technical side, the methodology requires some assumptions for estimating the active modal share and overall GIS parameterizing. In this article an *ansatz* for estimating the active modal share and a mean citizen approach for parameters were followed. It would be interesting in the future to validate the *ansatz* and to conduct a sensitivity analysis by segmentation of the population, e.g., by age group or socioeconomic status, which could affect destination weights and/or $p_{\mathrm{A}}(x)$ parameters to investigate what differences might arise. It is also worth noting that the active mode probabilities do not consider issues of interaction with motorized transport supply/demand, e.g., high motorized congestion might increase active trip probability. Investigating the impact of such interactions is another possible follow-up. We hope to pursue some of these lines of research in the near future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi12020048/s1, 1. Sensitivity Analysis on L_{kj} and job data statistics: Table S1; Active modal share summarizing statistics: Table S2. Modal share and fossil energy spending to jobs only. Table S3. Modal share and fossil energy spending to jobs only. 2. Full maps for L_{kj} = 70/20/10: (Figure S1a) Full cycling modal share to urban facilities; (Figure S1b) No cycling modal share to urban facilities; (Figure S2a) Full cycling modal share to urban facilities plus jobs; (Figure S2b) No cycling modal share to urban facilities plus jobs; (Figure S3a) Full cycling modal share to jobs; (Figure S3b) No cycling modal share to jobs; (Figure S4a) Full cycling fossil energy spending to urban facilities; (Figure S4b) No cycling fossil energy spending to urban facilities; (Figure S5a) Full cycling fossil energy spending to urban facilities plus jobs; (Figure S5b) No cycling fossil energy spending to urban facilities plus jobs; (Figure S6a) Full cycling fossil energy spending to jobs; (Figure S6b) No cycling fossil energy spending to jobs; (Figure S7a) Full cycling/no cycling modal share differential to urban facilities plus jobs; (Figure S7b) Full cycling/no cycling fossil energy spending differential to urban facilities plus jobs.

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