078

Easiest paths for walking and cycling:

Combining syntactic and geographic analyses in studying walking and cycling mobility

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Abstract

We discuss fundamentals of a new computational approach to configurative analysis and synthesis and present a number of advancements we have made in the direction of computational analysis of walking and cycling mobility. We have scrutinized the notion of distance and addressed it in correspondence with the notion of geodesic or optimum path. We present a new all-inclusive pathfinding algorithm for walking and cycling and show how this pathfinding algorithm can be used as a new basis for a number of conventional network indicators such as closeness and betweenness centrality measures -taking into account the physics of walking/cycling mobility as well as the cognitive aspect of human navigation. To this end, we revisit the meaning of distance and introduce a new notion of geodesic, which we call 'easiest path', i.e. a path that is reasonably short, flat and at the same time cognitively simple. Using this new geodesic, we reconstruct betweenness centrality indicator and introduce two new accessibility measures as 'proximity to any', 'vicinity of all' and a method of zoning as to walking and cycling accessibility. We show how suitability of locations as to their walking/cycling access can be modelled in a way that is immediately understandable for both citizens and urban designers/planners. Models are implemented as a toolkit, available as a freeware application.

Keywords

Street network, spatial configuration, accessibility, easiest path, walking and cycling

1. Introduction

In street network studies, there have been two main categories of street network representations, namely Junction-to-Junction and Street-to-Street graph representations –loosely speaking[A]. In the first category, street junctions are considered as nodes and streets as links, whereas in the second category, streets are considered as nodes and junctions as links between them. Geometrically, the former representation represents adjacencies between points (0-Dimensional features) and the latter represents adjacencies between lines (1-Dimensional features like axial line, centreline or a curve representing a street). This is of course an over-simplified way of describing these two categories; we refer the reader to a more extensive review of network representations for syntactic studies to (Batty 2004). In a Point-to-Point representation, which is as old as graph theory itself[B], it is quite straightforward to measure physical distance between locations and thus it is the de facto standard of transportation studies (Dios Ortuzar, J., & Willumsen, L. G. 2011). On the other hand, Space Syntax in particular and some other approaches such as Intersection Continuity Negotiation (Porta, S., Crucitti P., & Latora V. 2006) and Named Streets (Jiang, B., & Claramunt C. 2004) model street network as a Street-to-Street adjacency graph[C]. The immediate advantage of this approach to spatial network representation is that the notion of location is associated with streets and therefore the whole representation comes closer to the way people perceive their location in cities. In addition, cognitive aspects of way finding can be modelled more easily on Street-to-Street representations because usually there is cognitive impedance in going from one street to another, which affects way finding as in crossing a junction (the feeling of getting away from an origin) towards a destination. It sounds reasonable to attribute the relative success of Space Syntax in indicating pedestrian mobility to this fact; as walking requires intuitive way finding. It is important to note that Turner (Turner 2007) also builds his remarkable angular analysis method upon a Line-to-Line adjacency representation of street network. In spite of the differences between an axial line representation of a street by a centreline, (or other variations such as the one introduced by Jiang & Liu (Jiang B, Liu C 2009) these representations are all classifiable as Street-to-Street adjacency graph representations. The drawback of most of such representations is that the physical distance between locations is not taken into account.

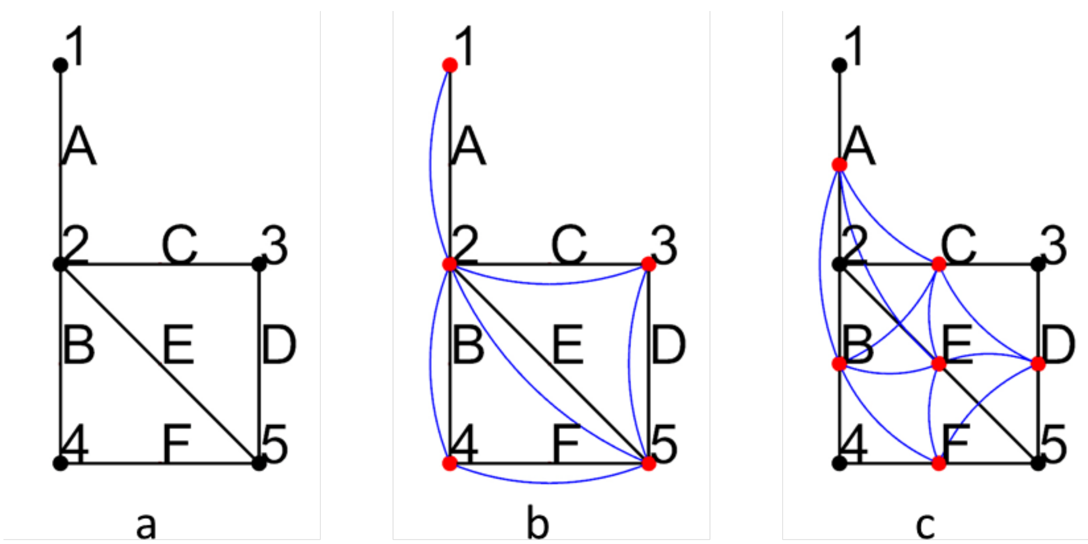

Figure 1 A hypothetical street network (a), a Junction-to-Junction adjacency graph (b) versus a Street-to-Street adjacency graph (c), both 'undirected', after Batty (Batty, 2004): red dots represent graph nodes, and blue arcs represent graph links.

We started our research with the assumption that in way finding for pedestrians and bicyclists and constructing a simulation model of walking/cycling flows, we need to take into account both the physical aspects of mobility and the cognitive aspects of way finding. Combining physical and cognitive aspects of way finding into a single model is previously researched by a few scholars as in the Multi-Modal Urban Network (Gil 2014), which is based on an undirected Street-to-Street graph representation, or Place Syntax (Ståhle A., Marcus, L. and Karlström, A. 2008), which combines topological distance with metric distance. In addition, Hillier and Ida (Hillier, B., & Ida, S. 2007) have compared different distance measures (metric, angular and topological). Building upon the work of Turner (ibid.) and (Duckham, M., and Kulik, L. 2003) we have constructed a new Street-to-Street 'directed' graph representation that incorporates both physical and cognitive distance into its graph definition. Based on this representation we form a new geodesic (optimal path) that we call the 'Easiest Path' for walking or cycling.

Space Syntax theories (Hillier, B., Hanson, J. 1984) and (Hillier 2007) relate the configuration of urban street network to urban functioning in terms of its effect on the distribution of densities and allocation of land uses such as retail and residence: "Land uses and building density follow movement in the grid, both adapting to and multiplying its effects." (Hillier 2007, p.127), stating that a spatially successful city is characterized by the "dense patterns of mixed use", which are mainly settled as a consequence of movement, which is itself "brought about by the grid configuration" (Hillier 2007, p. 4). However, two important aspects of built environments are not addressed in Space Syntax models and analyses, namely geographic attributes such as land-use and density[D] and the physical aspects such as steepness of routes. This paper is focused on the effects of the structure of built environment on walking and cycling; the structure seen as comprised of topology, geometry (regarding path continuity), topography and the possible weight of locations because of their spatial attributes such as population density and land-use attractions. To this end, we see walking and cycling as 'active' modes of transportation in which people actively interact physically, cognitively and socially with built environment. Therefore, for studying these activities, we will investigate the combination of syntactic analyses, which address the socio-cognitive aspects of walking and cycling, and the physical aspects such as the impedance of steep paths for walking and cycling. We regard physical ease of traveling as being related to how flat and short the path is; and cognitive ease of way finding can be thought of as how straightforward a path is or how close a destination appears to the mind of a traveller (another interpretation would be the ease of navigation from an origin to a destination). Pedestrians and bicyclists depend heavily on their physical strength for mobility. This strength can be boosted with electric bicycles to some extent; however, it is important to choose a path that is reasonably flat and short in distance; one's experience in walking and cycling would be much easier if path finding can be done intuitively, say without being totally dependent on availability of navigation and route planning services on mobile devices. These are all aspects that can be well studied on maps, given the availability of necessary geographic information. We formulate our main questions as follow:

- What would be a geodesic truly representative of best paths for walking and cycling, considering physical and cognitive aspects of these modes of transport?
- How can we study the structure of a neighbourhood (based on such geodesics) as to its suitability (accessibility of amenities) for pedestrians and bicyclists?

In search for comprehensive answers for the above questions, we have devised a computational model towards predicting and simulating walking and cycling flows. The model has parameters that need to be calibrated later by empirical research. We have implemented our model as a plugin toolkit (written in C# and VB.NET) for Mc Neel's Grasshopper© & Rhinoceros® CAD software application[E]. The tools are parametric and can be easily integrated with computational workflows. These tools can equip urban planners for studying walking and cycling accessibility of neighbourhoods.

2. Way-Finding Essentials for Walking and Cycling

There are several criteria affecting one's choice of walking and cycling routes, which might have different levels of importance. In order to have an all-inclusive model we need to study each factor as cost attributes on a street-to-street adjacency graph representation. The nodes of this graph are directed street segments (see Figure 2) and the links between them bear the cost/impedance values as explained further.

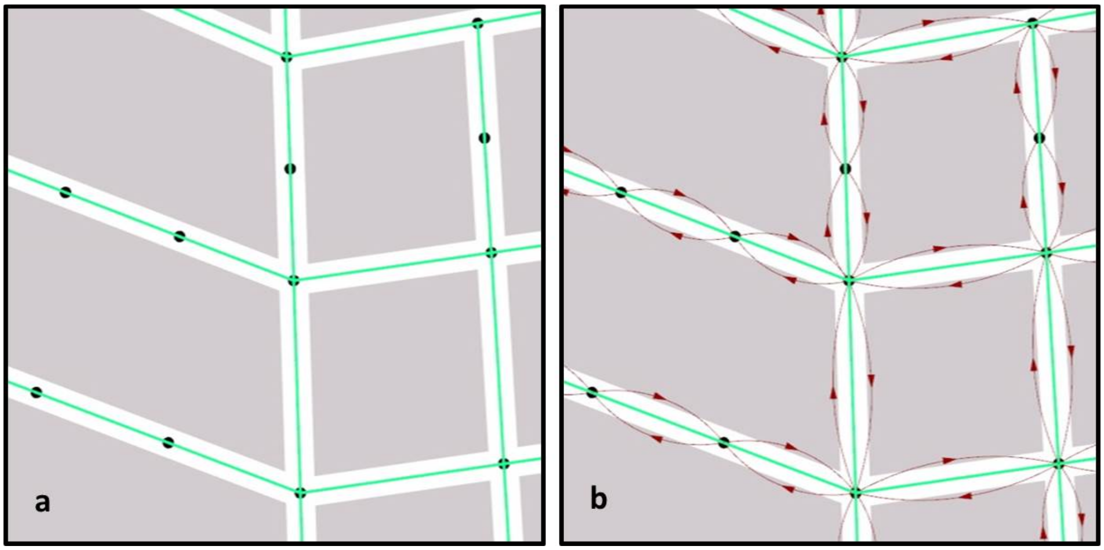

Figure 2 (a) shows the street centrelines shattered into segments no longer than a maximum length value defined by the user; (b) each segment is converted to two oppositely directed line segments shown as arcs. These directed lines become the nodes of our graph representation and the links between them get the physical and cognitive cost or impedance attributes as explained in the followings. The links between these nodes are not shown because they would have been too complicated to be perceived visually. Further technical details of the Easiest Path algorithm do not fit the scope of this paper; therefore, they will be published in a forthcoming paper.

Physical Difficulty: Length Impedance

When walking or cycling, people depend heavily on their physical strength, this limitation determines the effective speed of walking or cycling that is easy to maintain and thus affects the temporal distance to certain destinations and eventually willingness to take or not to take certain routes. We can calculate such mobility speeds and relate them to the slope of road segments by taking into account the physical power that a normal person can easily maintain. Obviously, this power would be a parameter that can be adapted to represent the conditions of those with less strength or those riding on power-assisted bikes such as e-bikes. Without loss of generality, we assume that an average person can maintain a power of around 100 Watts easily for about an hour or so. Walking speed has been modelled as a function of slope by Waldo Tobler (Tobler 1993) as shown in **Figure 1**. Inspired by the model of Tobler (ibid), and the illuminating blog article of Rhett Allain (Allain 2013) on the physics of cycling, we have formulated a model of cycling speed as a function of slope angle (only uphill slopes for the time being).

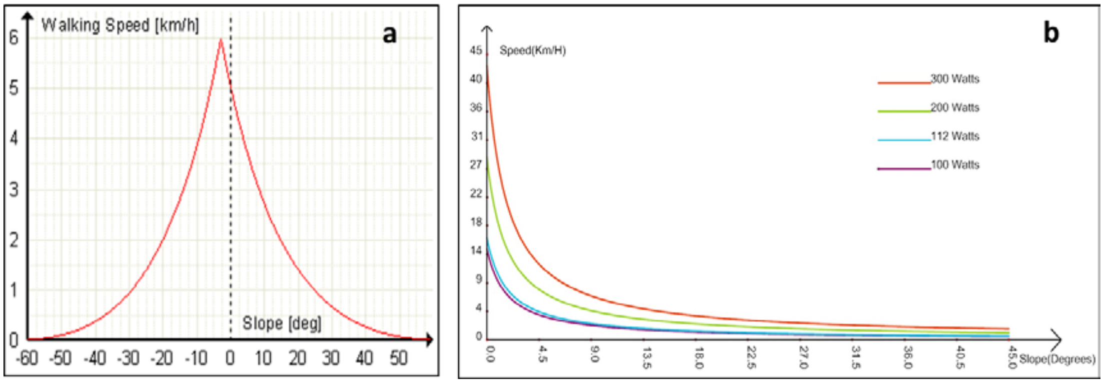

Figure 3 Picture (a) shows a graph of Tobler's hiking function. Note that at the slope of 0 the walking speed is 5 Km/h. Also, note that on downhill slopes humans do not walk much faster. In fact, a little bit of downhill slope boosts walking speed but too much of downhill slope slows down walking. Picture (b) shows plots of our model of cycling speed as a function of slope at the constant power of 112 Watts, which is approximately 0.15 HP, a power that an average human can easily sustain for about two hours.

The ultimate intention is to obtain a model of temporal cost of traversing a segment in terms of its slope angle. We consider such costs as impedances physically hindering biped mobility and denote them as WI_k and CI_k as for walking impedance and cycling impedance of the k^{th} link. In these equations, δ represents the displacement along the k^{th} link and α_k denotes the slope angle of the link in radians, m the mass of an average person typically assumed to be 75 Kilograms and g for gravitational acceleration equal to 9.81 m/s^2, and F_f denoting a nominal force of friction that is to be counteracted by the bicyclist[F].

$$WLI_k := WLI_k(\alpha_k) = \frac{\delta}{WV_k} = \frac{3.6\delta}{6e^{-3.5|\tan\alpha_k + 0.05|}} = \frac{3.6\delta e^{3.5|\tan\alpha_k + 0.05|}}{6} \qquad \text{Equation 1}$$

$$CLI_k := CLI_k(\alpha_k) = \frac{\delta}{CV_k} = \frac{\delta(mg\sin\alpha_k + F_f)}{P} = \frac{\delta(85 \times 9.81 \times \sin\alpha_k + 25)}{112} \qquad \text{Equation 2}$$

The two impedances WI_k and CI_k are computed in terms of [average] seconds it takes one to traverse a link. We need to note that we have not yet considered the higher speed of pedestrians or bicyclists on downhill roads.

Cognitive Difficulty: Angular Impedance

We consider change of direction or turning at each junction, as a cognitive kind of impedance for a pedestrian or bicyclist traversing that link. We denote angular impedance of k^{th} link as AI_k. In order to compute this, we need to find the angles between nodes (street segments); then we need to attribute impedance values corresponding to these angles consistently. We find the angles as shown in Figure 4. In order to make the dimension of AI_k commensurate[G] with those of WI_k or CI_k we need to introduce a 'temporal confusion' coefficient in terms of the seconds it would take a person to take a decision as to which street incident to the junction has to be followed next. By adjusting this parameter, denoted as τ, we can distinguish between those who know the neighbourhood well from newcomers and tourists. It is important to note that in our method we have chosen to disregard angular impedance for streets of degree 2 or less (at junctions in between only two street segments or dead-ends) because, we believe that they do not cause any significant cognitive impedance compared to junctions between multiple streets where making a choice requires a bit of thinking. In other words, streets of less than three neighbours (streets of degree 2 or 1) lead to only one other street on a side therefore cause no confusion when it comes to directionality.

In search for a sigmoid function that could accept arguments of type radians, we concluded that squared sine of theta times the arbitrary confusion coefficient τ works consistently as a relative impedance function, besides converting angles measured in Radians to dimensionless numbers. For the time being, we choose an arbitrary amount of 10 seconds for average confusion time in case of maximum change of directionality. This parameter could be calibrated by further empirical research.

$$AI_k := AI_k(\varphi_k) = \begin{cases} \tau \sin^2 \frac{\theta_k}{2} : \tau = 10 \text{ seconds, if } \mathrm{Deg}(l_k) > 2 \\ 0 \quad otherwise \end{cases}$$ Equation 3

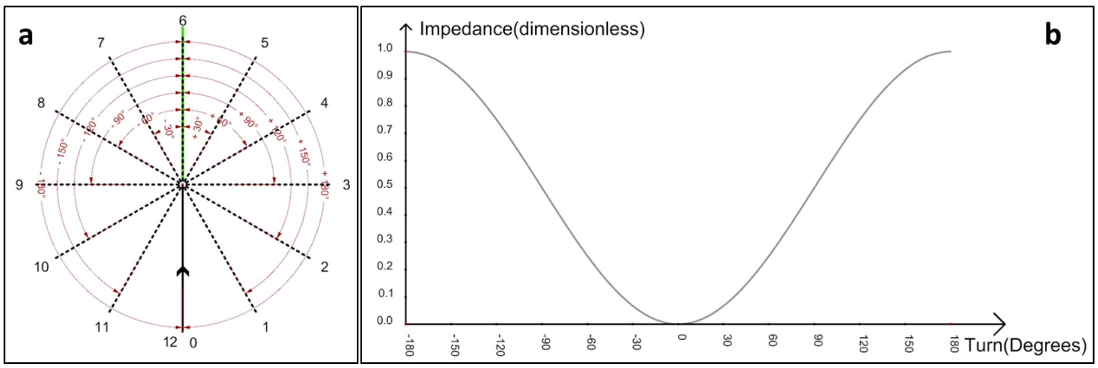

Figure 4 Picture (a) shows how the angles are computed for different hypothetical destination streets, given the directed origin street shown in bold black. Note that going from the origin to destination number 6 corresponds to no change in direction and thus zero degrees of turn and no impedance at all. Note also that changing movement direction does not make any difference in angles computed. Picture (b) shows a plot of the turning (cognitive) impedance function as a dimensionless normalized factor.

Walking/Cycling Geodesic, EASIEST PATH

We will present the technical details of our Easiest Path algorithm in a forthcoming paper; here, we give an overview of what it takes to find optimal paths using the impedance measures introduced above and show examples of such geodesics on an urban network. We model the street network as a directed graph that has directed street segments (segments of street centrelines) as nodes and their junctions as links. In this graph, we minimize the impedance of travelling from an origin to a destination. As we have defined both cognitive confusion and physical difficulty in terms of time, they are commensurate and therefore we can use a weighted sum model to model the total impedance of each link. The geodesics are then found using a graph search algorithm. Formally, the algorithm minimizes the total impedance of a path between an origin and a destination (i^{th} node to j^{th} node). A path is defined as a sequence of nodes (i.e. street segments) $\pi = (n_1, n_2, \ldots, n_m) \in N \times N \times \ldots \times N$ such that n_j is adjacent to n_{j+1} for $1 \leq j < m$. The path π is said to be of length m from the first node (n_1) to the last node (n_m). Having defined a real-valued impedance/cost function $f: L \to \mathbb{R}$, which attributes an impedance or cost to each link of the graph $\Gamma_d(N, L)$, we need to find a path $\pi = (n_1, n_2, \ldots, n_m)$ that minimizes the total cost or impedance of going from an origin n_o to a destination n_d ($n_o = n_1, n_d = n_m$) over all possible paths between n_o & n_d. Let $L_{i,j}$ be the link in between n_i & n_j, then we need to minimize the following sum (with reference to our prior definitions of impedance): (note that we have denoted the cost function $f(L_k) = \zeta_k$ [H]. In our formulation we have considered weights of importance for temporal and angular impedances to account for different preferences of tourists or residents.

$$\sum_{j=1}^{m-1} f\left(L_{j,j+1}\right) = \sum_{k\in L\cap\pi} \zeta_k = \sum_{k\in L\cap\pi} W_L . LI_k + W_A . AI_k \qquad \text{Equation 4}$$

$$W_L + W_A = 1, \qquad 0 \leq W_A, W_L \leq 1, \qquad LI_k = \begin{cases} WLI_k, & Walking \\ CLI_k, & Cycling \end{cases} \qquad \text{Equation 5}$$

The choice of weights might seem as arbitrary; however, they are in fact parameters of the simulation models to be calibrated later by empirical research using pedestrian and bicyclist movement GPS tracks obtained from mobile devices, aggregated spatially and temporally over a period of one year.

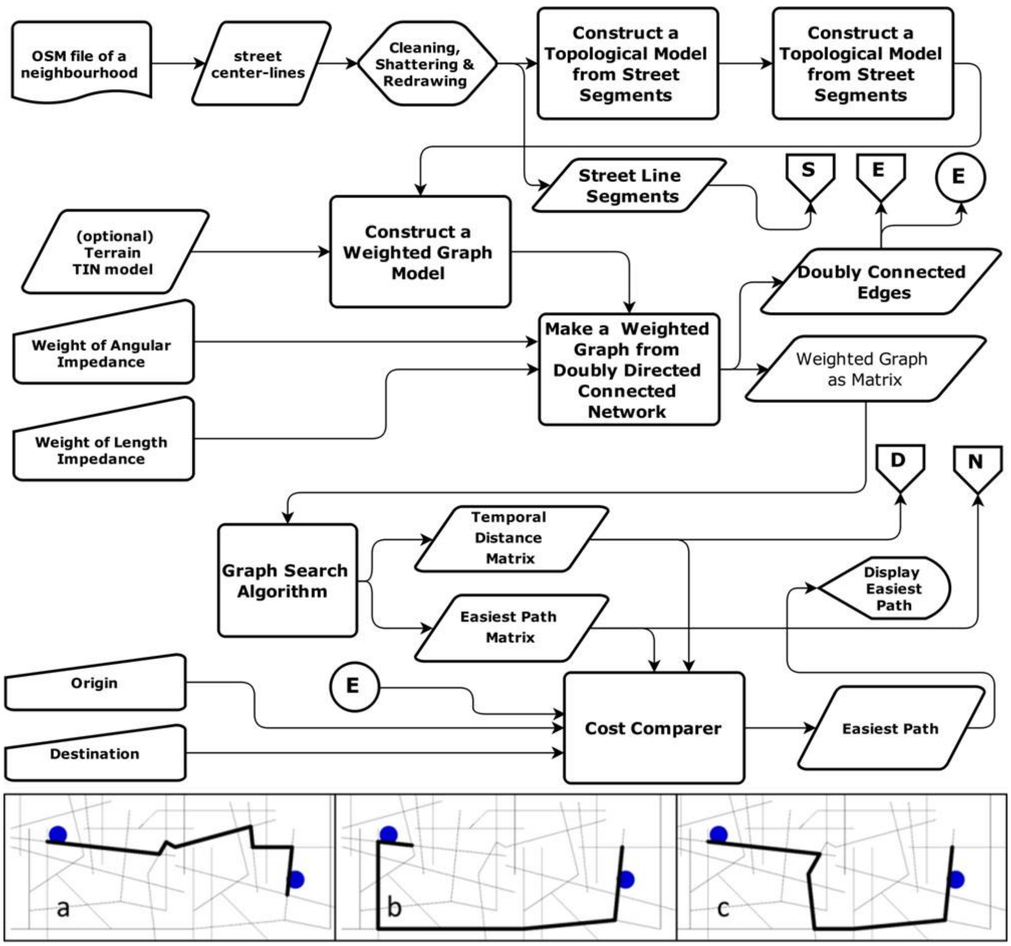

Figure 5 (top) the modules of the toolkit (implemented in C# for Grasshopper©) that construct such a graph, search it and find geodesics (easiest paths) between origins and destinations. The "Easiest Path" computed with different weights for physical and cognitive impedance on a hypothetical street network: (a) zero weight of angular impedance, (b) zero weight for temporal impedance, and (c), equal weights of both angular and temporal impedances[I].

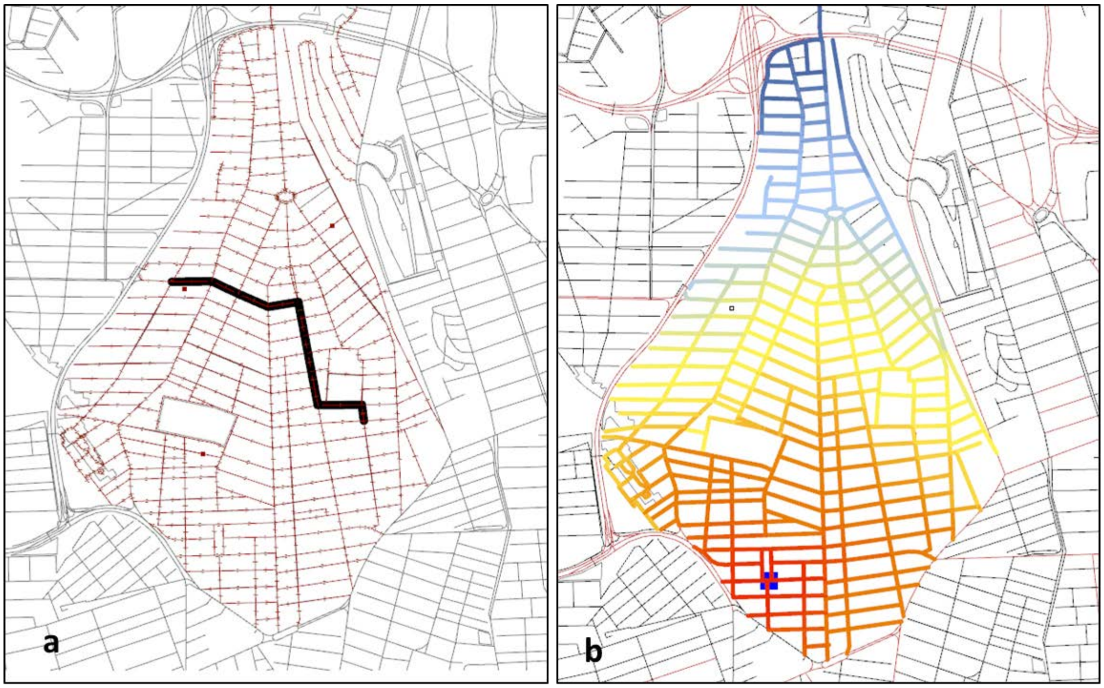

Figure 6 the hilly middle-class neighbourhood of Yousef Abad in Tehran from OSM (Open Street Map). Altitude difference between the two ends of the longest street in North-South direction is about 140 Metres. Picture (a) shows an easiest path between an origin and a destination, in which angular impedance and temporal impedance have had equal weights. Picture (b) shows a map of access time (temporal distance, only physical impedance) to all destinations from a chosen origin marked as a blue square: the redder the colour the closer a destination and the bluer the farther.

3. Walking/Cycling Accessibility

For studying accessibility, we have chosen to formulate measures that are understandable for lay citizens and planners equally. Having constructed our graph and computed the easiest path, we have introduced a class of accessibility indicators namely Vicinity, Proximity, Catchment Areas (only redefined) and Catch Zones based on the geodesics computed. Given a set of land-use attraction points noted as POI (points of interest):

- **VICINITY:** What is the accessible/reachable area of t minute walking or cycling from **any of them**? We have answered this question by introducing a measure called "vicinity of any" or **vicinity** in short.
- **PROXIMITY:** What is the accessible/reachable area of t minute walking or cycling from **all of them**? We have answered this question by introducing a measure called "proximity to all" or **proximity** in short.
- **ZONE:** How can we divide a neighbourhood in zones such that the people living in each zone have a better/preferred access to one of the attraction points? For example, how can we divide a neighbourhood in zones of walking/cycling access to a set of grocery stores? We have introduced spatial zones in which every location closer to its corresponding POI than any other POI. This is a variant of Weighted Voronoi[J] diagrams on a set-based geometry.

All these measures are weighted so as to represent the relative land-use importance of the POI. This is similar to the approach to that of (Karimi 2012) in combining land-use weights with syntactic analyses.

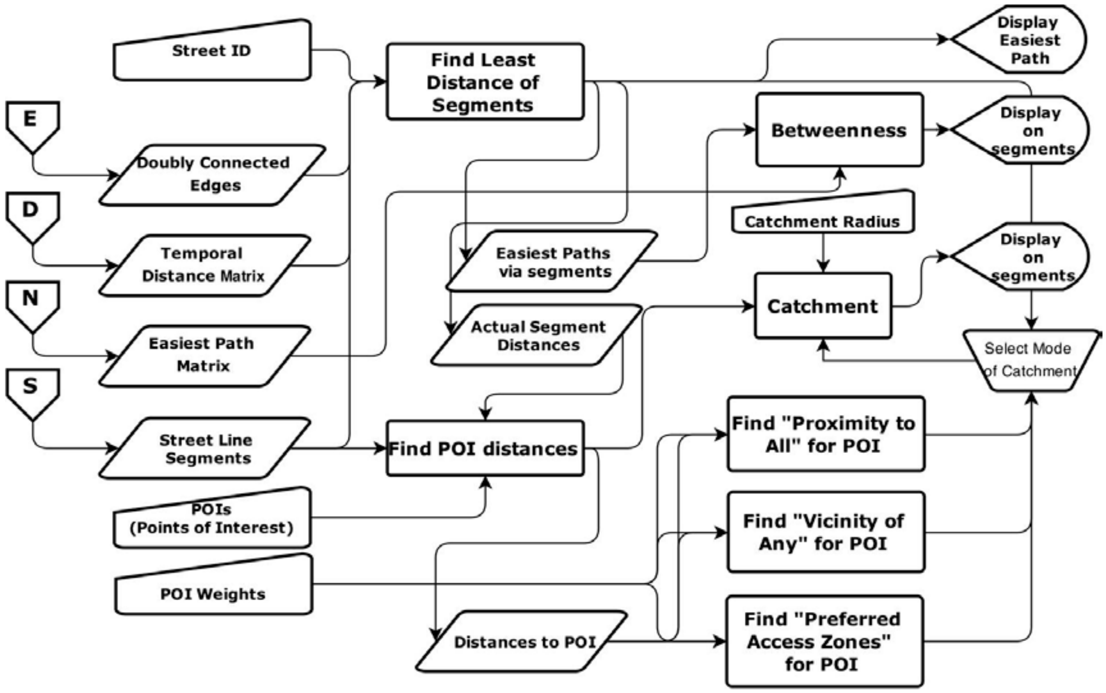

Figure 7 Accessibility modelling components implemented in C# for Grasshopper©[K]

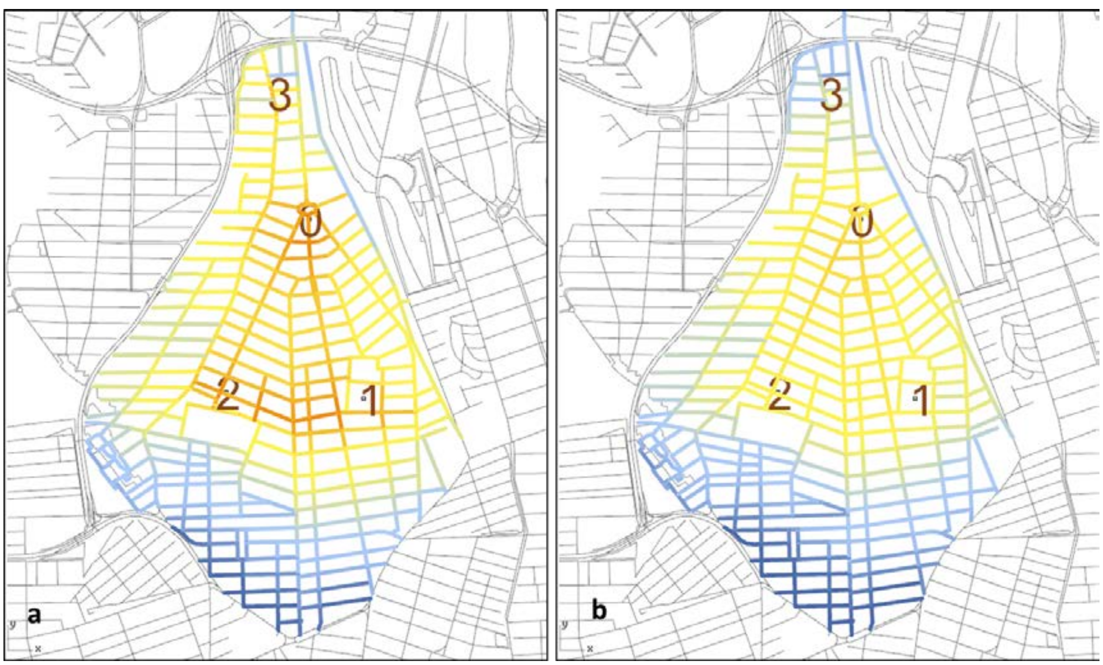

Figure 8 vicinity of any when (a) all points have the same importance and a 30 minutes walking distance is considered as near and above it as far; and (b) the same situation when above 10 minutes walking distance is considered as relatively far.

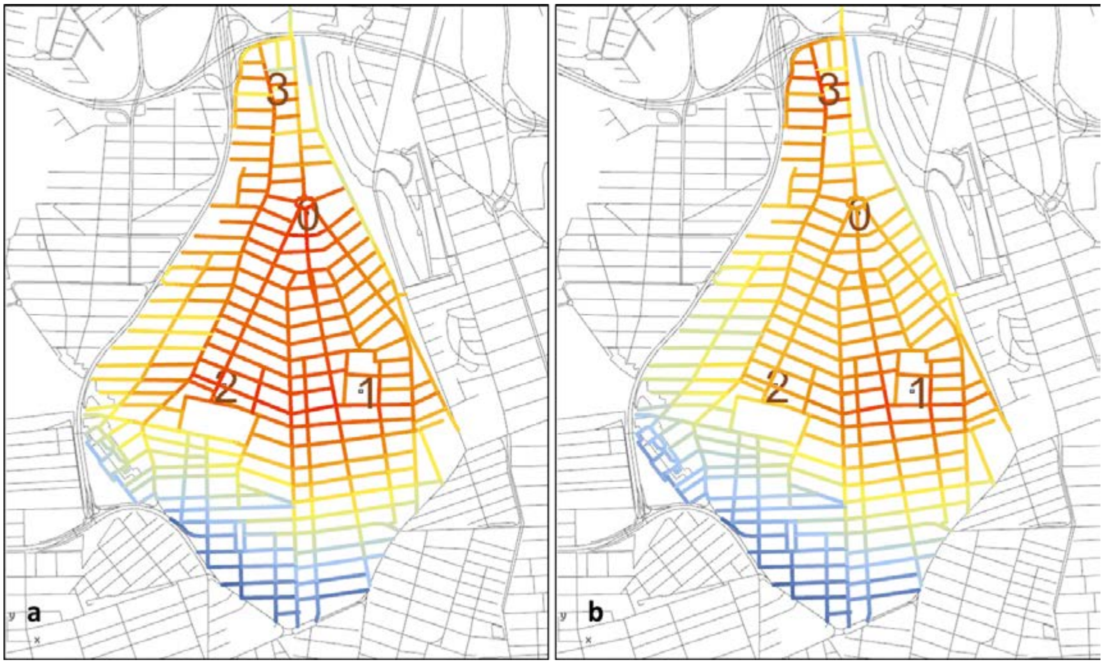

Figure 9 proximity to all when (a) all POI have the same weight and (b) when 0 and 2 have less importance

Figure 10 (a) zones of preferred POI when all are equally important; (b) when 2 and 0 are less important

Temporal Distance versus Spatial Distance

We can see that time is a better measure of convenience compared to path length, when it comes to measuring distances for pedestrians and cyclists. Temporal distance is the natural outcome of our geodesic algorithm, because we have defined all costs in terms of time. This is quite useful in making sense out of analyses; because we can easily compare trips in terms of their temporal length and thus their practicality. We can for instance suppose that walking or cycling more than 1 hour is not practical for most people, then a node of temporal distance more than one hour will be regarded as absolutely far; but the distances less than 1 hour will be relatively near.

4. Walking/Cycling Centrality

Space Syntax indicators such as Integration (a variant of closeness centrality) and Choice (betweenness centrality) are both defined based on different notions of 'geodesics' or shortest paths, be it topological shortest path or angular shortest path. We can reconstruct such indicators by substituting these geodesics with Easiest Path for network studies focused on walking and cycling. Here we focus on betweenness centrality as it can be interpreted as the probability that people would pass through a certain street going from some place to another, while they are following an easiest path. This is of course of importance for retail businesses as they depend on the probability of passage of pedestrians. Similar to all other indicators, in computation of centrality measures we can opt for equal weights of physical and cognitive impedances or change them to take account of preferences of people who care more for shortness of routes or those who prefer simpler routes.

It is interesting for planning professionals to know what would be the effect of a change in the network in terms of the pedestrian or cyclist flows. The measure of 'betweenness' was introduced by Linton Freeman as an indicator of importance of nodes in a social network (Freeman 1977). Considering all shortest paths in a network between all possible pairs of nodes, we can find out how often a node happens to be on a shortest path between two other nodes. We can interpret this as the probability that a person passes through a certain street segment given all other possibilities. Variations of this model based on angular shortest paths or metric shortest paths have been found to have high correlations with the location of businesses such as retail, cafes and pubs (examples mentioned in (Hillier 2007) & (Sevtsuk 2010)). The new element in our model is the geodesics we have introduced as the most convenient paths for pedestrians and cyclists. As is the case with any model, our model is based on a reduction of complex reality so it can never perfectly explain how people find some routes more convenient (or pleasant) and actually take them from their origins to their destinations. The reality is of course more complicated due to many other decision variables, many of which are perhaps related to the functional aspects of urban trips.

The probability interpretation leads us to consider dividing interesting possibilities by the total number of possibilities; therefore, we divide the total number of geodesics that include the node in question by the total number of all geodesics. Given that the graph is connected, then the total number of geodesics equals the total number of pairs of origin-destination. This corresponds to the number of combinations of two nodes from all nodes, excluding the node in question. We can define the bare probability of passage of a body through a node (in absence of attractions and other information) as in Equation 7 , in which γ_{st} is the geodesic path between source s and target t and $\sigma(s, n_i, t)$ is a binary variable that is equal to one if the geodesic γ_{st} (i.e. a sequence of nodes) contains the node in question (n_i). Note that this is a simplification of the original Betweenness Centrality as defined by Freeman; because we have assumed it is very unlikely that there exist more than one geodesic in between a pair of nodes. A similar simplification, for a similar reason is used in (Turner 2007).

$$|\{(s,t)|s \in N, t \in N, s \neq i \neq t\}| = \binom{|N|-1}{2} = \frac{(|N|-2)\times(|N|-1)}{2} \quad \text{Equation 6}$$

$$B(n_i) = \frac{2 \times \sum_{s=1}^{|N|}\sum_{t=1}^{|N|}\sigma(s,n_i,t)}{(|N|-2)\times(|N|-1)} \mid s \neq i \neq t, \sigma(s,n_i,t) = \begin{cases} 1, if \ \gamma_{st} \ni n_i \\ 0, otherwise \end{cases} \quad \text{Equation 7}$$

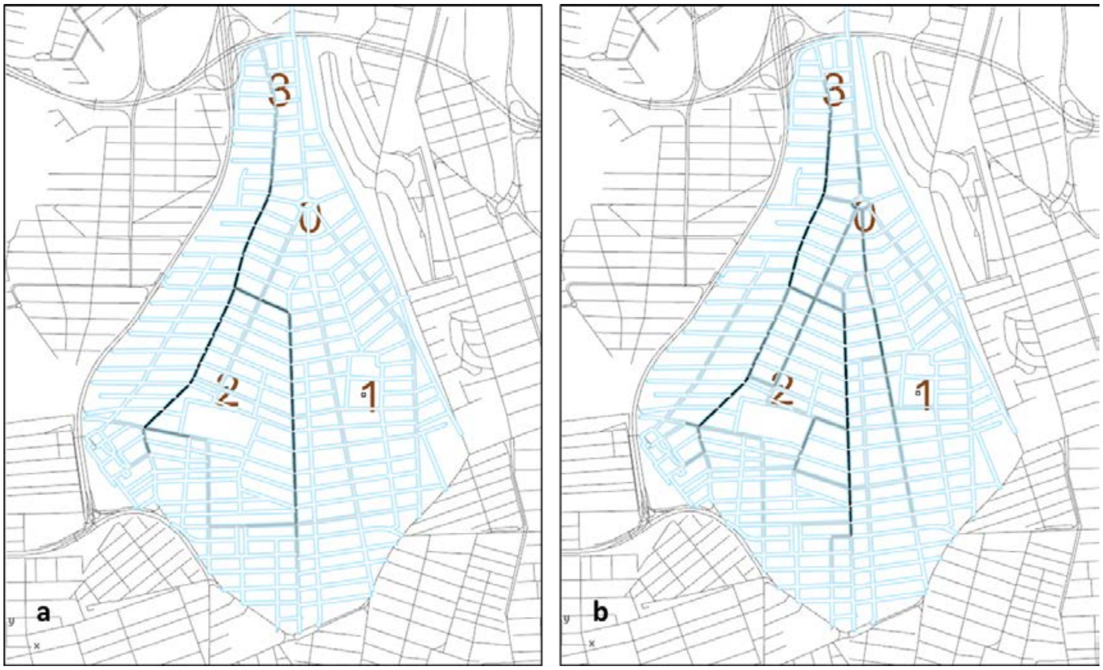

Figure 11 (a) shows the betweenness centrality when the geodesic is only angular and the weight of physical distance is zero; and (b) shows betweenness centrality when both angular and temporal impedances have been given equal weight. It is visible that the picture (b) takes better account of reality as to importance of main roads of the neighbourhood have been revealed better compared to the case (a) when the algorithms disregards the physical distance.

5. Discussion

We have constructed an algorithmic notion of a geodesic as most convenient for walking or cycling named as Easiest Path. This geodesic provides for a more comprehensive network analysis as to the suitability of a network for walking and cycling. This is because any such geodesic is computed taking into account not only by accounting for physical distance on a 2D map but also the walking/cycling speed as to the slope of road segments, besides the cognitive impedance of turning at junctions. Any such geodesic is a path that can be recommended to a pedestrian or bicyclist guaranteeing that the suggested path is the most convenient, meaning it is as flat, short and straightforward as possible. We have defined a number of accessibility measures based on this geodesic that arguably are understandable for both lay citizens and planners. Namely, walking or cycling time to any point of interest or to all points of interest or the zones of preferred access to any point of interest; points of interest being representatives of land-use attraction points (e.g. grocery/convenience stores) are measures that play a role in daily decision-makings and also real estate market.

What is innovative in this method is the use of a new street network representation, which allows for combining different impedances to take account of flatness, shortness and straightness of a path. This provides a basis for finding the most convenient paths by combining aspects that used to be measureable separately on different representations, but were never together in one framework. Using conventional spatial network representations, one can either focus on metric aspects or cognitive aspects but not both systematically seen together. It is also remarkable that we have considered topography for computing most convenient paths. Although this point is not so visible in our images yet, due to the coarse resolution of the digital terrain model that was available to us. Furthermore, we have generalized the hiking impedance function of Tobler to cycling impedance; this allows for modeling actual behavior of urban cyclists. These methods and models can be used for navigation applications aimed at guiding pedestrians and cyclists by proposing convenient paths that are easy to remember (being straightforward), as well as a decision support tool suite for urban planners.

We are aware that the actual decision-making of people in way finding is more complicated than being based on our easiest path and is affected by perceived safety, security, pleasance, road quality and perhaps attractions such as shops throughout routes they might take. We believe considering these additional parameters deserves deeper methodological research accompanied by empirical research into actual movement patterns obtained through web/mobile applications that collect GPS tracks of people. For this purpose, we believe such data of tracks needs to be aggregated temporally and spatially in order to be representative of the normal movement patterns. In absence of such data, most of previous researchers have used data sets that only include hours of movement data collected. Given the availability of reliable unbiased data over long terms and many cities, we see a great potential in researching actual movement patterns. Many people are sceptical about predictive urban models, perhaps rightly so, however, we believe that such models are needed to provide insight into planning actions. Every model will be wrong in the absolute sense of the word but we can think of models that can better explain the complex behaviour of people in built environment and thus come useful in assessing plans.

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[A] Previously, they have been categorised as primal and dual representations. We consider this distinction merely as a meta-label to categorise two large lines of works. However, the terms do not bear the exact meaning of Poincare duality in topology. In fact, what we are interested in is the distinction between spatial network models that model the connection between spaces as links from those, which model spaces as links between spatial junctions.

[B] The graph model of bridges of Konigsberg by Leonhard Euler (1707-1783) had bridges represented as links and lands as nodes.

[C] The spatial network representation of space syntax graph that is based on axial lines is in fact a particular class of visibility graphs. Further discussion on this topic is not in the scope of this paper.

[D] They consider the so-called "natural movement" (Hillier, B., Penn, A., Hanson, J., Grajewski, T. & Xu, J. 1993)

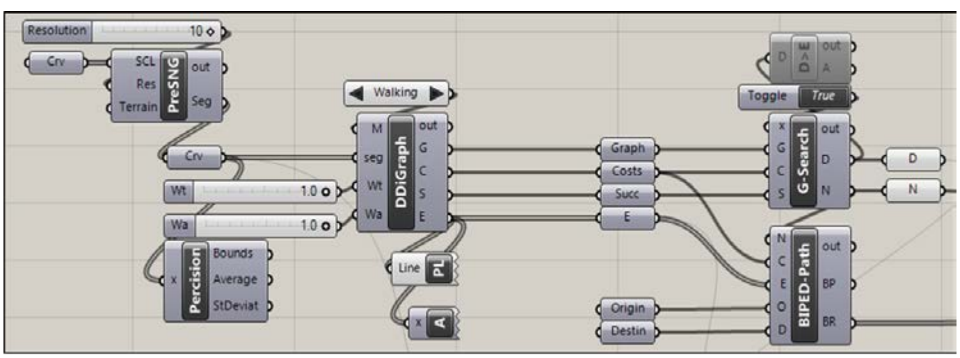
[E] The forthcoming version of the toolkit CONFIGURBANIST: https://sites.google.com/site/pirouznourian/configurbanist

F The details of these models are discussed in a forthcoming book chapter in Research in Urbanism Series, to be published by TU Delft, faculty of Architecture and the Built Environment.

G It might seem easy to add angles to meters of distance but that would be physically wrong, just like adding peers and apples. When two quantities are added, they need to have the same physical dimensions and units. This issue is referred to as unit commensurability in physics.

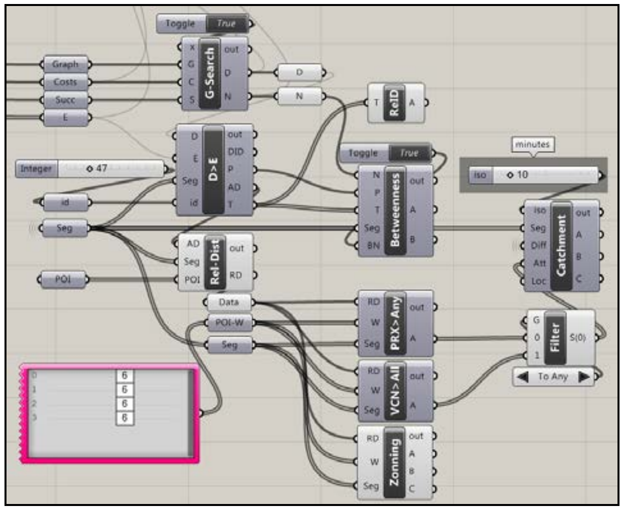
H Finding the link index (k) of for the link $L_{i,j}$ we can get the cost of each link from the pre-calculated impedance set.

[I] The Easiest Path components as implemented in VB.NET and C# for Grasshopper©; they can be integrated in other workflows:



[J] First defined by Georgy Voronoy (1868-1908) based on Euclidean distance. We have generalized the notion of Voronoi regions by replacing the Euclidean distance with the Easiest Path distance.

[K] The Accessibility Analysis components as implemented for the visual programming interface of Grasshopper©


Toggle
True
G-Search
Graph
Costs
Succ
E
D
N
RelD
Integer
47
id
Seg
D>E
Toggle
True
Betweenness
minutes
Iso
10
Catchment
Rel-Dist
POI
Data
POI-W
Seg
PRX>Any
Filter
To Any
VCN>All
Zonning